CARBON MINERALIZATION ROADMAP

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PREFACE

This ninth ICEF roadmap explores a topic that has received too little attention: the potential for carbon mineralization to play an important role in helping fight climate change.

Carbon mineralization is a natural process in which carbon dioxide (CO_2) becomes bound in rocks as a solid mineral, permanently removing the CO_2 from the atmosphere. This process could provide the foundation for many activities that not only help fight climate change by removing additional CO_2 from the atmosphere, but create jobs and deliver local environmental benefits as well. Resources for carbon mineralization are abundant and located in dozens of countries around the world.

This roadmap builds on the body of literature produced annually in connection with the ICEF conference. Previous roadmaps have addressed:

- Biomass Carbon Removal and Storage (BiCRS) (2020)
- Industrial Heat Decarbonization (2019)
- Direct Air Capture (2018)
- Carbon Dioxide Utilization (2017 and 2016)
- Energy Storage (2017)
- Zero Energy Buildings (2016)
- Solar and Storage (2015)

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The ICEF Innovation Roadmap Project aims to contribute to the global dialogue about solutions to the challenge of climate change. We welcome your thoughts, reactions and suggestions.

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EXECUTIVE SUMMARY:

Chapter 1. **INTRODUCTION TO CARBON MINERALIZATION**

According to the Intergovernmental Panel on Climate Change (IPCC), significant volumes of carbon dioxide (CO_2) must be removed from the atmosphere for the world to achieve its climate goals.

One approach for CO_2 removal that has received relatively little attention is ***carbon mineralization***, a process in which CO_2 becomes bound in rocks as a solid mineral. Carbon mineralization happens naturally when certain rocks are exposed to CO_2, permanently removing roughly 0.3 $GtCO_2$ from the atmosphere each year.

There are two broad approaches to increasing the amount of CO_2 removed from the atmosphere via carbon mineralization: injecting CO_2-rich fluids into rock formations deep underground (*in situ* mineralization) and exposing crushed rocks on the Earth's surface to CO_2-bearing gases (*ex situ* or surficial mineralization).

As a strategy for CO_2 removal and sequestration, carbon mineralization has many strengths. First, mineralization resources are effectively unlimited and located in dozens of countries around the world. Second, carbon mineralization offers one of the most permanent forms of CO_2 removal and sequestration available, binding CO_2 into solid rock. Third, the chemical reactions that mineralize CO_2 do not require energy inputs. Finally, the costs of carbon mineralization appear to be reasonable and could be reduced.

There are also several challenges with using carbon mineralization for CO_2 removal and sequestration. First, most natural carbon mineralization happens very slowly. Second, the distribution of optimal mineral resources is only coarsely understood. Third, while some products of carbon mineralization have commercial value, those values are typically low. Finally, carbon mineralization for climate mitigation is not yet practiced at large scale.

The authors estimate that, with strong and sustained policy support from governments around the world, carbon mineralization processes could remove 1 $GtCO_2$ from the atmosphere per year by 2035 and 10 $GtCO_2$ per year by 2050. More research is needed to test this hypothesis and define conditions under which carbon mineralization could achieve this potential.

Chapter 2. **SCIENCE PRIMER**

Rocks are one of the Earth's largest carbon reservoirs. CO_2 is transferred from the atmosphere into rocks in part through a process known as chemical weathering. (CO_2 is also transferred from the atmosphere into rocks via photosynthesis, where carbon from marine organisms eventually forms limestones and other carbon-rich rocks.) Engineered carbon mineralization processes seek to replicate and accelerate this natural process.

Several types of rocks are very well suited to carbon mineralization because they weather rapidly and contain the right elements to form long-lived carbonate minerals, namely magnesium (Mg) and calcium (Ca). Such rocks include ultramafic or mafic igneous rocks and the ultramafic metamorphic rock serpentinite. These rocks are abundant at or near the Earth's surface.

Chapter 3. **UNDERGROUND INJECTION**

In situ mineralization is the process of injecting CO_2 into subsurface mafic or ultramafic rocks. The CO_2 reacts with surrounding rocks to form solid, stable carbonates. Rocks suitable for *in situ* mineralization are abundant and geographically widespread.

Two projects have demonstrated *in situ* mineralization to date: the Wallula pilot project in Washington State, US and the CarbFix project in Iceland. Both use CO_2 captured from point sources. Additional and larger-scale field projects are the next logical step toward demonstrating that the technology can scale to volumes that meaningfully contribute to climate mitigation.

Chapter 4. **ENHANCED ROCK WEATHERING**

Enhanced rock weathering (ERW) involves dispersing ultramafic or mafic rock powder over large areas, such as agricultural fields. Calcium- and magnesium-bearing minerals in the rock powder then react with atmospheric CO_2, trapping the CO_2 in groundwater and solid carbonates.

ERW offers gigaton-scale capacity to capture and permanently store CO_2. The main advantages of ERW are the simplicity of the approach, consistency with current mining and agricultural practices, and co-benefits that may include improved soil fertility in some areas. The main challenges of ERW are the lack of widely accepted methodologies for determining CO_2 removal rates and concerns about environmental risks from accumulation of metals, including nickel and chromium.

Chapter 5. **MINING WASTES**

Some waste rock from mining could be reacted with CO_2 to form stable carbonates. These mining wastes could provide hundreds of millions of tons per year of CO_2 removal across dozens of countries. In addition, billions of tons of stockpiled mining wastes are already available as a feedstock for carbon mineralization. National and regional geological surveys are needed to map these resources and assess their carbon mineralization potential and reactivity. Methods for monitoring and measuring CO_2 uptake into mining wastes already exist, but a recognized international standard for verifying CO_2 sequestration of mining wastes is needed.

Carbon mineralization can also be used as an ore processing technology that improves recovery of critical metals for clean energy technologies. Demonstration projects are underway for accelerated carbon mineralization in mining wastes, but more industry-government-university collaborations on research and development (R&D) will be needed to bring this technology to scale.

Chapter 6. **INDUSTRIAL WASTES**

Some industrial wastes from iron and steel production, coal combustion and fertilizer production could provide billions of tons of alkaline feedstock each year for carbon mineralization. In some cases, mineralizing these wastes would significantly reduce the cost and environmental impact of their disposal. However, in industrialized countries a large portion of this waste is already used in ways that have a climate benefit. Careful system analysis is needed to identify the climate impacts of alternative uses.

The largest potential for industrial waste as a carbon mineralization feedstock is in China, followed by India. Effective use of industrial wastes for mineralization will require additional applied research and demonstration because wastes are highly varied and mineralization processes have not yet been developed at scale.

Chapter 7. **CEMENT AND CONCRETE**

Billions of tons of cement and concrete are produced annually, contributing approximately 8% of global emissions. Carbon mineralization could reduce these emissions, through three primary pathways: mixing carbonation, carbon curing and synthetic aggregates. These three pathways have each seen early-stage commercial deployments, mostly at a small scale

In general, these mineralization techniques are compatible with other methods for reducing cement and concrete emissions, including the use of supplementary cementitious materials to displace clinker, the use of electric or hydrogen-fired kilns to reduce thermal emissions, and the use of point-source carbon capture. In principle, the use of mineralization in combination with these other mitigation methods could lead to fully carbon-negative concrete under certain circumstances, an important prospect given the enormous size of the global cement and concrete industry.

Chapter 8. **CROSS-CUTTING RESEARCH NEEDS**

R&D needs in carbon mineralization focus on increasing the speed with which the reactions occur, accessing a significant volume of reactive material (surficial or subsurface), disposing of carbonate material produced via surficial methods, measuring the total carbon impact of these approaches and improving the economics of the processes. Significant cross-cutting issues are water use and safety from potentially toxic and hazardous components present in both minerals and industrial wastes.

R&D on these topics should be supplemented by work on system integration, energy efficiency and cost reduction. Large-scale demonstrations are vital for addressing these needs across all forms of carbon mineralization.

Chapter 9. **POLICY**

Policymakers have paid scant attention to carbon mineralization as a strategy for fighting climate change. For carbon mineralization to remove gigatons of CO_2 from the atmosphere each year, that must change.

Supportive policies will be essential. That could include funding in government R&D budgets, preferences in government procurement and incentives in tax regimes. Recognition of carbon mineralization as a compliance option in emissions trading programs is one of the most important potential tools. International cooperation—including programs to share information and jointly conduct demonstration projects—could accelerate progress.

Regulatory issues will also require considerable attention. Carbon mineralization projects may be subject to regulations on diverse topics, including groundwater protection, hazardous waste management, foreign ownership and financial transparency. Governments could support pilot and demonstration projects to help assess regulatory issues. Relevant ministries and departments could examine the overall regulatory environment for carbon mineralization projects. Policy frameworks that engage key stakeholders will be essential.

Chapter 10. **COMPARISONS WITH DIRECT AIR CAPTURE**

The term “direct air capture” (DAC) is generally used to refer to engineered methods that remove CO_2 from air with synthetic sorbents or solvents. As a strategy for removing CO_2 from the atmosphere, carbon mineralization shares many characteristics with DAC. Both are early stage and currently expensive. Both have clear pathways to reduce costs, can be deployed in many locations around the world and show considerable promise in helping achieve net-zero emissions.

The two strategies also have important differences. Most carbon mineralization processes require less energy than DAC. Some carbon mineralization processes offer ancillary benefits not available from DAC. However, measurement and verification of CO_2 removal is more difficult for most carbon mineralization processes than for DAC. Since several DAC demonstration projects are currently operating or under construction, while just a few carbon mineralization methods have been verified at a pilot scale, more scientific research is required for full deployment of carbon mineralization than for DAC.

Chapter 11: **FINDING AND RECOMMENDATIONS**

FINDINGS

FINDING 1: Carbon mineralization has the potential to permanently remove and sequester many gigatons of CO_2 from the atmosphere each year.

FINDING 2: As a strategy for carbon removal and sequestration, carbon mineralization has many strengths.

FINDING 3: As a strategy for carbon removal and sequestration, carbon mineralization also has several challenges.

FINDING 4: Carbon mineralization is not one pathway—it is multiple pathways.

FINDING 5: Carbon mineralization receives little recognition or support in climate change policies around the world.

FINDING 6: Current scientific knowledge and technical experience are sufficient to support carbon mineralization projects at the pilot and demonstration scale today.

FINDING 7: The key technical challenges in carbon mineralization are (1) speeding up the chemical reaction between atmospheric CO_2 and minerals, (2) maximizing the CO_2 content of mineralized materials and (3) minimizing the space required for permanent storage.

FINDING 8: Measurement and verification tools today are sufficient for some carbon mineralization approaches (including *ex situ* conversion of mine tailings) and insufficient for others (including enhanced rock weathering).

FINDING 9: Field pilots and demonstration projects could significantly improve understanding of the potential impacts and costs of carbon mineralization processes, while improving monitoring and verification methods.

RECOMMENDATIONS

RECOMMENDATION 1: *Policy makers should add carbon mineralization to the portfolio of climate change mitigation options.*

RECOMMENDATION 2: *Governments and companies should invest in R&D on carbon mineralization.*

RECOMMENDATION 3: *Mining companies and manufacturers should seek opportunities for carbon mineralization in their exploration and production activities.*

RECOMMENDATION 4: *Governments and companies with net-zero commitments should consider carbon mineralization as part of their portfolio of options.*

CHAPTER 1:

INTRODUCTION TO CARBON MINERALIZATION

The concentration of heat-trapping gases in the atmosphere is now higher than at any time in human history and continuing to climb.

Dozens of countries, representing more than 70% of global emissions, have now made net-zero pledges. Yet the path to achieving these net-zero pledges is uncertain at best. While steep declines in the cost of renewable power and energy storage offer hope for decarbonizing the global power sector, pathways for decarbonizing other sectors, including industry, aviation and agriculture, are far less clear.[1]

And time is short. The heat waves, floods, droughts and wildfires in the past year highlight the enormous and growing risks of climate change.[2] To prevent even more dangerous impacts, emissions must fall quickly in the decades ahead.

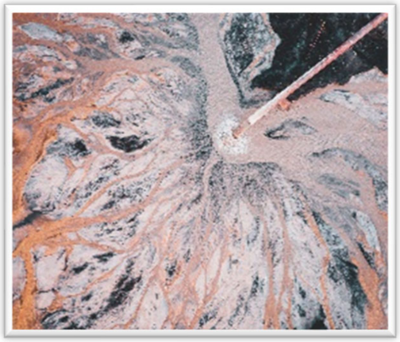
However falling emissions will not be enough. For the world to achieve its climate goals, significant volumes of CO_2 must also be removed from the atmosphere. As the Intergovernmental Panel on Climate Change (IPCC) found in its 1.5 °C report, "All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century."[3] Approaches such as direct air capture (DAC) of CO_2, biomass carbon removal and storage (BiCRS), and afforestation will be essential.[4]

Carbon Mineralization: The Basics

One approach for CO_2 removal that has received relatively little attention is *carbon mineralization*, a process in which CO_2 becomes bound in rocks as a solid mineral. Carbon mineralization happens naturally when certain rocks are exposed to CO_2, which then binds with calcium (Ca), magnesium (Mg) or other elements in these rocks to form "carbonate minerals." The CO_2 in the carbonate minerals is trapped in a solid, stable and non-toxic form, in which it is permanently removed from the atmosphere.

Carbon mineralization is a natural process that removes roughly 0.3 Gt CO_2 from the atmosphere each year.[5] The main goal of the carbon mineralization processes discussed in this report is to increase this amount. Two approaches are possible:

- In the first, CO_2-rich fluids are injected underground into rock formations. This approach is known as *in situ* mineralization
- In the second, CO_2-bearing gases are exposed to crushed rocks, such as mine tailings or industrial wastes, on the Earth's surface. This is known as *ex situ* or surficial mineralization



In both approaches, CO_2 is permanently incorporated into minerals. There are differences between the two approaches, including in cost, ease of verification and operational needs.

Strengths

The strengths of carbon mineralization as a climate mitigation strategy are enormous.

First, the potential capacity of the mineralization resource is effectively unlimited. Estimates of the gross CO_2 removal capacity of carbon mineralization range from many trillions to quadrillions of tons of CO_2.[6,7] In addition, mineral resources that can be used for CO_2 removal are available in substantial quantities in many countries around the world (Figure 1).[8] The sheer abundance and wide dispersion of carbon mineralization resources means that many nations and companies could use carbon mineralization as a CO_2 reduction and removal strategy at scale.

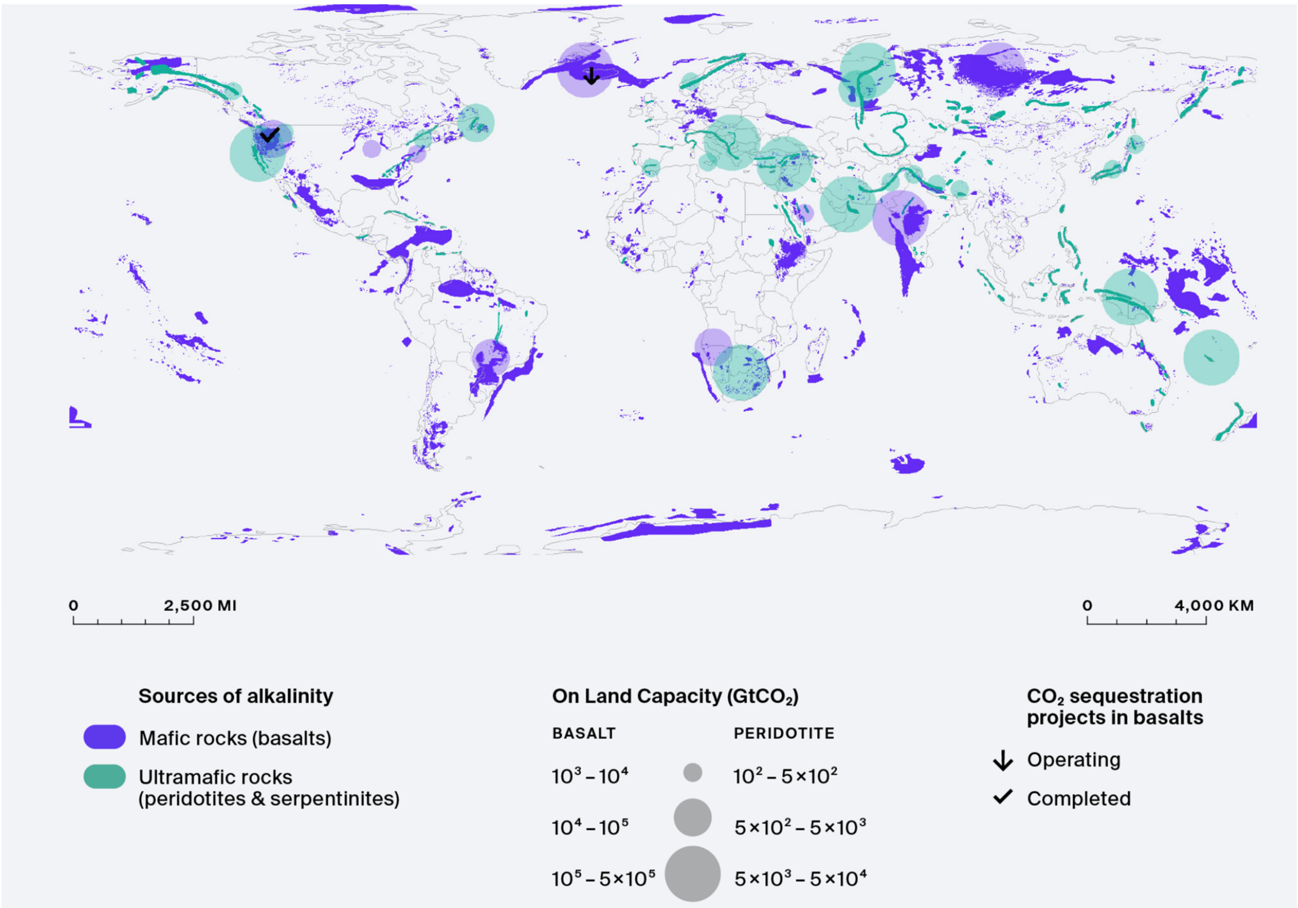


Figure 1.1 Locations and distribution of carbon mineralization resources. Source: CDR Primer, Chapter 3, 2021.[9]

In addition, some industrial wastes provide CO_2 mineralization opportunities.[9] Such wastes include steel slag, fly ash and phosphogypsum. These wastes are often located at industrial facilities and/or near CO_2 sources. In some cases, carbon mineralization of geological resources or industrial wastes can yield building materials with economic value, such as concrete aggregate.

Second, carbon mineralization offers the most permanent form of CO_2 removal and sequestration available, binding CO_2 into solid rock. Although some other carbon removal strategies (such as reforestation) can provide many important benefits, including biodiversity protection, such strategies often risk release of CO_2 back into the atmosphere on short timescales (such as through forest fires). This risk is essentially absent with carbon mineralization.

Third, the chemical reactions that mineralize CO_2 do not require energy inputs. In fact, spontaneous carbon mineralization reactions generate heat. As a result, carbon mineralization strategies generally do not compete for energy resources and often have minimal operating expenses (although special-purpose reactor vessels, heat and other reagents may be needed to accelerate key reactions in the near term as the relevant technologies mature and scale).

Finally, the costs of carbon mineralization appear to be reasonable and could be reduced. Estimates today range widely—from \$10–1000/tCO_2 removed—as a function of resource quality and process characterization.[10] There are many options to reduce costs through operational improvements, novel engineering and better chemistry. New projects (like CarbFix[11]) and new companies (like Heirloom Carbon Technologies[12]) are providing more information on real costs and opportunities to improve them.

As a result of these features, carbon mineralization has the potential to remove CO_2 from the atmosphere at a scale of gigatons per year. A number of peer-reviewed studies have found that ~1–10 $GtCO_2$ per year could be removed from the atmosphere globally from *ex situ* mineralization of mine tailings and industrial wastes alone.[10-18] In most of these studies, the timeframe in which technology could be deployed to achieve these removals is unclear.

Challenges

For carbon mineralization to reach its full potential as a climate change mitigation strategy, several important challenges must be overcome.

First, most natural carbon mineralization happens very slowly, consuming available magnesium and/or calcium at rates of a few percent per year or less. This process can be accelerated via grinding or "reaction-driven cracking" to increase the surface area of minerals; drilling to accelerate subsurface CO_2 delivery; or the addition of heat, acid or other reagents. However, these steps can add cost as well as produce CO_2 emissions. Reducing these costs and CO_2 emissions is a key focus of ongoing carbon mineralization research.

Second, the distribution of mineral resources appropriate for carbon mineralization remains only coarsely understood. Although the location of rock types most favorable for carbon mineralization (including ultramafic rocks and basalt) is broadly known, the ability to use these geologic resources for mineralization of CO_2 at scale requires more granular information on the concentrations, compositions and volumes of minerals at specific locations. This will require substantial new geologic resource assessment and characterization.

Third, while some products of carbon mineralization have commercial value, those values are typically low, creating little incentive to invest or change existing practices. For this reason, policy support is needed to accomplish the widespread adoption and implementation of carbon mineralization.

Finally, carbon mineralization for climate mitigation is not yet practiced at large scale, and new challenges will likely be identified in the future. Fortunately, many related practices, such as mining, rock grinding and wellbore injection, are in widespread use around the world, suggesting the foundations for large-scale carbon mineralization already exist in many places.

How Many Gigatons of Carbon Removal by When?

One important question is the timeframe in which carbon mineralization could deliver significant rates of carbon removal. Some prior research has considered carbon mineralization's potential for carbon removal at scale, with leading estimates in the range of 1–10 $GtCO_2$ per year.[13-21] However the literature is mostly silent on the length of time required to deploy the infrastructure needed for these removals. An important reason for this silence is that the factors determining how quickly carbon mineralization could be scaled up largely depend on policy decisions, including the level of incentives and willingness of governments to streamline regulatory barriers.

We considered how quickly carbon mineralization could remove CO_2 from the atmosphere if governments were strongly committed to supporting it as a climate change mitigation strategy. In that scenario, companies that decided to pursue large-scale carbon mineralization operations would need to (1) buy or lease processing equipment, (2) hire a trained workforce, (3) obtain land and (4) secure a source of both mineral feedstock and CO_2. For *ex situ* mineralization methods, companies would also need to secure offtake or disposal options for mineralized products.

The processing equipment required for most mineralization methods is very similar or identical to equipment already in widespread use in the mining, oil and gas, and agriculture industries. An extensive manufacturing base for this equipment already exists in many countries, and very little specialized or non-commodity equipment would be needed. This suggests that obtaining the required equipment for mineralization would not be a significant bottleneck to scale-up.

Similarly, the skills required for jobs in carbon mineralization are similar to the skills required for jobs in the mining and oil and gas sectors. As a result, a well-trained labor pool for carbon mineralization projects already exists in many places. Carbon mineralization projects could help protect jobs in communities in which employment opportunities in the mining and oil and gas sectors are shrinking.

Obtaining land and mineral feedstocks could represent a larger challenge for companies seeking to scale carbon mineralization. While *in situ* and some *ex situ* mineralization methods are not highly land-intensive, some surficial methods require large tracts of land (although not for exclusive use). In some cases, looping reagents (CaO and/or MgO derived from rocks) through multiple cycles of CO_2 removal from air and/or stacking material for ambient weathering could reduce land use requirements significantly. Even so, identifying appropriate sites and obtaining rights to this land could be time-consuming. Obtaining community acceptance, particularly for methods that use significant land area, would be imperative. In general, carbon mineralization methods that use degraded or unused land (potentially former mine sites or other industrial land) would be likely to encounter fewer challenges to rapid scale-up. Mineral feedstocks for *ex situ* methods could be sourced from mining or industrial wastes or from virgin rock. Access to

these resources would depend on regulatory permission, which could emerge as a principal bottleneck to rapid scale up.

Access to CO_2 could prove challenging for rapid scale-up of some methods. Mineralization methods requiring pure CO_2 would need to either capture and transport it from point sources or use methods such as DAC to remove it directly from the air. Successful scale-up of mineralization would require a careful matching between CO_2 sources and mineralization feedstock, and either could serve as the limiting factor or bottleneck under different circumstances. *In situ* methods that use atmospheric CO_2 dissolved in surface waters could face challenges related to securing sufficient water. *Ex situ* methods that produce valorized products, such as aggregates, would need to secure buyers, but these markets are large and unlikely to saturate quickly.

Taking all these factors into account, we believe there are no technical barriers to scaling carbon mineralization methods to capture and/or store billions of tons of CO_2 per year. Most proposed methods use existing technology that is already in widespread use with known costs. However, for carbon mineralization to reach its full potential as a climate mitigation strategy, strong and sustained policy support will be needed. While emphasizing the significant uncertainty about the potential pace of scale-up, we estimate that, with strong and sustained policy support from governments around the world, carbon mineralization processes have the potential to remove 1 $GtCO_2$ from the atmosphere per year by 2035 and 10 $GtCO_2$ per year by 2050. These estimates are based on the authors' expert judgment. More research is needed to test this hypothesis and define conditions under which carbon mineralization processes could achieve this potential.

Path Forward

Interest and investment in carbon mineralization is growing.[22-24] In large part this is due to increasing recognition that an enormous amount of CO_2 must be removed from the atmosphere to achieve global climate goals, such as those set forth in the Paris Agreement. As a result, new companies pursuing CO_2 removal via carbon mineralization have come on the scene, and investment in this approach for CO_2 removal has increased.[11,12,25] One technology company, Stripe, has purchased very small volumes of CO_2 removal through carbon mineralization.

Yet the use of carbon mineralization as a climate change strategy is tiny in relation to its potential. One reason is a chronic underfunding of research and development (R&D) related to carbon mineralization.[26] Another is the absence of carbon markets in many jurisdictions, meaning that the carbon removal service of carbon mineralization often has little commercial value, making it difficult for projects and new companies to gain investors. Beyond the lack of R&D funding and carbon markets, policy makers and businesses generally lack understanding of carbon mineralization or its potential to contribute to achieving net-zero emissions.

Ultimately, policy decisions will be crucial in determining the rate of scale-up for carbon mineralization. It is worth noting that the world has observed an extraordinary example of technology scale-up over the past two years in another field—public health. Given the enormous pressures to act in response to the COVID-19 pandemic, governments mobilized resources and streamlined regulations in order to scale production of multiple vaccines—some of which were based on unproven technologies—from zero to billions of doses in less than 24 months. This example illustrates how quickly new technologies can be deployed if political will is strong. Although there are important differences between carbon mineralization and vaccines, the example is instructive. The urgency of the climate crisis should inspire policy makers to proceed with carbon mineralization and other low-carbon technologies on an urgent basis.

In that spirit, this ICEF Roadmap provides background on carbon mineralization's potential for climate change mitigation and recommends steps to help achieve that potential. The roadmap discusses scientific and technological aspects of carbon mineralization for CO_2 removal and storage, as well as system-level characterization and optimization challenges. It explores different approaches, feedstocks and business models and compares carbon mineralization as a climate change mitigation strategy with DAC. The roadmap provides a set of cross-cutting research priorities and policy options for scaling up carbon mineralization. The final chapter offers findings and recommendations.

REFERENCES

1 The International Energy Agency (IEA). *Net Zero by 2050*, <https://www.iea.org/reports/net-zero-by-2050> (IEA, Paris; 2021).

2 Christopher Flavelle, Anne Barnard, Brad Plumer & Michael Kimmelman. *Overlapping Disasters Expose Harsh Climate Reality: The U.S. Is Not Ready*, <https://www.nytimes.com/2021/09/02/climate/new-york-rain-floods-climate-change.html> (NY Times; 2021).

3 Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5 °C: Headline Statements from the Summary for Policymakers*, <https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Headline-statements.pdf> (2019).

4 David Sandalow, Julio Friedmann, Colin McCormick & Sean McCoy. *ICEF Roadmap 2018: Direct Air Capture of Carbon Dioxide*, <https://www.icef.go.jp/pdf/2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf> (Innovation for Cool Earth Forum; 2018).

5 P. Ciais *et al. Carbon and Other Biogeochemical Cycles (in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change)*. ((eds. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley) Cambridge University Press; Cambridge, United Kingdom and New York, NY, USA, 2013).

6 National Academies of Sciences (Engineering and Medicine) (NASEM). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. (Washington, DC: The National Academies Press, 2019; https://doi.org/10.17226/25259).

7 Energy Futures Initiative. *Rock Solid: Harnessing Mineralization for Large-Scale CarbonManagement.*, <https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/6011a6b8633ac2604c92a022/1611769538335/Rock+Solid.pdf.pdf> (December 2020).

8 J Wilcox, B Kolosz & J Freeman. *CDR Primer*, <https://cdrprimer.org > (2021).

9 Heping Xie *et al.* Scientific and Engineering Progress in CO2 Mineralization Using Industrial Waste and Natural Minerals. *Engineering* **1**, 150-157, doi:https://doi.org/10.15302/J-ENG-2015017 (2015).

10 Engineering National Academies of Sciences & Medicine. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. (The National Academies Press, 2019).

11 CarbFix. <https://www.carbfix.com> (Accessed September 2021).

12 Heirloom Carbon Technologies. <https://www.heirloomcarbon.com/> (Accessed September 2021).

13 David J. Beerling *et al.* Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature* **583**, 242-248, doi:10.1038/s41586-020-2448-9 (https://www.nature.com/articles/s41586-020-2448-9) (2020).

14 Peter Kelemen, Sally M. Benson, Hélène Pilorgé, Peter Psarras & Jennifer Wilcox. An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations. *Frontiers in Climate* **1**, doi:10.3389/fclim.2019.00009 (2019).

15 Noah McQueen, Peter Kelemen, Greg Dipple, Phil Renforth & Jennifer Wilcox. Ambient weathering of magnesium oxide for CO2 removal from air. *Nat. Commun.* **11**, 3299, doi:10.1038/s41467-020-16510-3 (2020).

16 Corey Myers & Takao Nakagaki. Direct mineralization of atmospheric CO2 using natural rocks in Japan. *Environ. Res. Lett.* **15**, 124018, doi:10.1088/1748-9326/abc217 (2020).

17 Corey A. Myers, Takao Nakagaki & Kosei Akutsu. Quantification of the CO2 mineralization potential of ironmaking and steelmaking slags under direct gas-solid reactions in flue gas. *Int. J. Greenh. Gas Control* **87**, 100-111, doi:https://doi.org/10.1016/j.ijggc.2019.05.021 (2019).

18 Hesam Ostovari, André Sternberg & André Bardow. Rock 'n' use of CO2: carbon footprint of carbon capture and utilization by mineralization. *Sustainable Energy & Fuels* **4**, 4482-4496, doi:10.1039/D0SE00190B (2020).

19 Shu-Yuan Pan *et al.* CO2 mineralization and utilization by alkaline solid wastes for potential carbon reduction. *Nature Sustainability* **3**, 399-405, doi:10.1038/s41893-020-0486-9 (2020).

20 Phil Renforth. The negative emission potential of alkaline materials. *Nat. Commun.* **10**, 1401, doi:10.1038/s41467-019-09475-5 (2019).

21 Caleb M. Woodall, Noah McQueen, Hélène Pilorgé & Jennifer Wilcox. Utilization of mineral carbonation products: current state and potential. *Greenhouse Gases: Science and Technology* **9**, 1096-1113, doi:https://doi.org/10.1002/ghg.1940 (2019).

22 Devin Coldewey. *44.01 secures $5M to turn billions of tons of carbon dioxide to stone*, <https://techcrunch.com/2021/08/10/44-01-secures-5m-to-turn-billions-of-tons-of-carbon-dioxide-to-stone/> (TechCrunch; August 2021).

23 Douglas Fox. Rare Mantle Rocks in Oman Could Sequester Massive Amounts of CO2. *Scientific American* **325, 1**, 44-53, doi:10.1038/scientificamerican0721-44 (https://www.scientificamerican.com/article/rare-mantle-rocks-in-oman-could-sequester-massive-amounts-of-co2/) (July 2021).

24 James Temple. *A startup using minerals to draw down CO2 has scored funding—and its first buyer*, <https://www.technologyreview.com/2021/05/26/1025402/heirloom-stripe-breakthrough-energy-lowercarbon-carbon-removal/> (MIT Technology Review; May 2021).

25 44.01. <https://4401.earth/> (Accessed September 2021).

26 Varun Sivaram, Colin Cunliff, David Hart, Julio Friedmann & David Sandalow. Energizing America: A Roadmap to Launch a National Energy Innovation Mission. (Columbia School of International and Public Affairs – Center on Global Energy Policy; 2020).

CHAPTER 2:

SCIENCE PRIMER

Rocks are one of the Earth's largest carbon reservoirs. Rocks in the Earth's crust contain about 100,000 trillion tons of carbon (~370,000 trillion tCO_2), mostly in the form of carbonate minerals.[1]

Crustal rocks incorporate carbon in part through a process known as chemical weathering. CO_2 in the atmosphere dissolves into rain and surface water—similar to the way CO_2 is dissolved in carbonated beverages. The dissolved CO_2 in water forms a weak acid called carbonic acid (H_2CO_3). This acid then dissolves minerals in rocks, releasing ions including calcium (Ca), magnesium (Mg) and sodium (Na). Some of these ions react locally with dissolved CO_2 to form carbonate minerals, while others are carried by rivers to the ocean where they precipitate in carbonate minerals—such as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$) and natron (mixtures of hydrated sodium carbonates)—that accumulate on the ocean floor to form sedimentary rocks, such as limestone and evaporites.

(Crustal rocks also contain carbon removed from the air via photosynthesis. See, for example, limestones, black shales, and oil and gas reservoirs.)

Through chemical weathering, CO_2 is transferred from the atmosphere to carbonate minerals, where the CO_2 is stored over long timescales. CO_2 is released from carbonate rocks—also over long

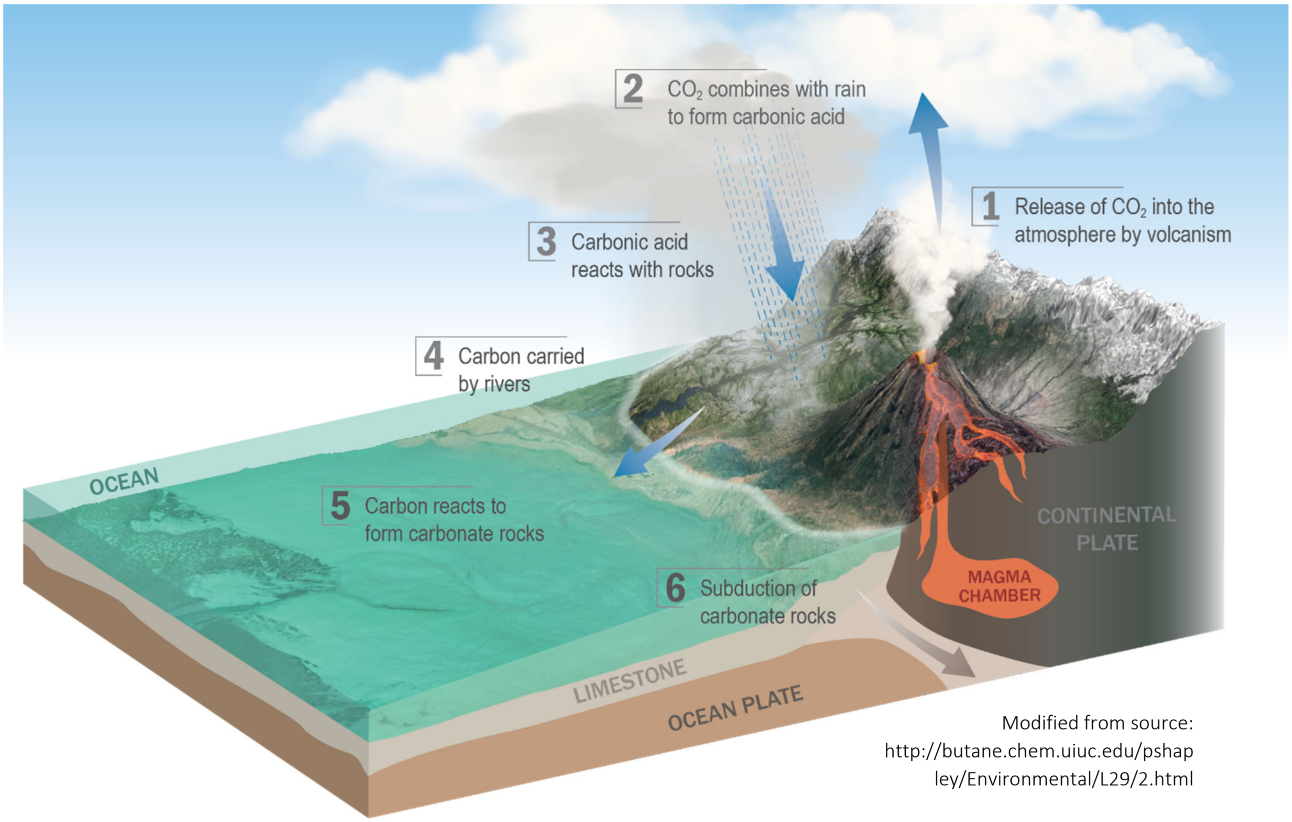


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Figure 2.1. Slow Carbon Cycle.

timescales—when those rocks are carried underground into the Earth's mantle in subduction zones. Heat and pressure in the mantle cause carbonate minerals to react, releasing CO_2 from the minerals. Some of this CO_2 eventually re-enters the atmosphere through volcanic eruptions.

The natural process of chemical weathering is part of the so-called "slow carbon cycle," which is estimated to draw down about 0.3 billion tons of atmospheric CO_2 per year.[2] Over long timescales this drawdown is approximately balanced by the amount of CO_2 released from volcanoes, such that the average amount of CO_2 in the atmosphere stays roughly constant. In contrast, human activities release more than 40 billion tCO_2 every year. Carbon mineralization practices seek to speed up the natural process of chemical weathering to draw down more atmospheric CO_2.

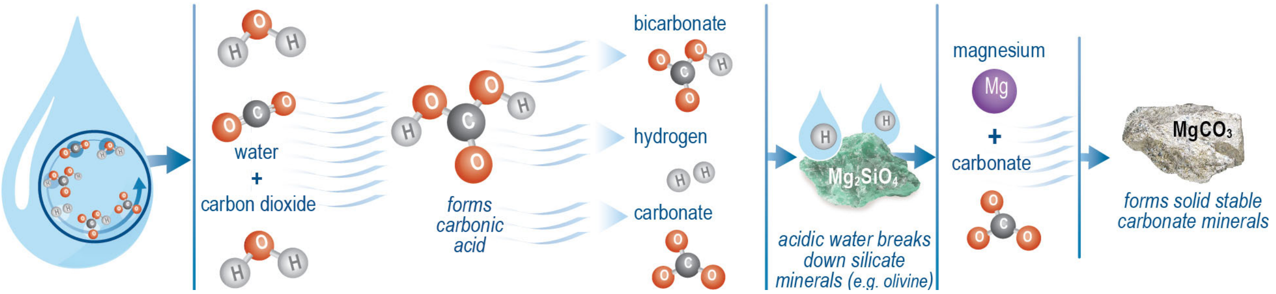


Figure 2.2. Following carbon molecules through the mineralization process.

Three primary factors can limit the natural rate of chemical weathering: mineral dissolution, CO_2 supply and carbonate formation.[3,4] Each of these factors are in turn impacted by a number of other factors.

- Mineral dissolution rates depend on average temperature, humidity, precipitation, the surface area of the mineral exposed to the atmosphere and other factors.
- Even though human activities have greatly increased atmospheric concentration of CO_2, that concentration is still relatively low overall (0.04%), which limits the amount of CO_2 available for chemical weathering processes. In the subsurface, dissolved carbon contents in circulating fluids depend on pressure and temperature. Carbon delivery to sites of mineral dissolution and precipitation depends on factors including fluid flow rates, which in turn are controlled by permeability, pressure gradients, fluid viscosity and—on a small scale—diffusivity.
- The rate of carbonate mineral precipitation depends on factors including pH, temperature and availability of cations, such as magnesium (Mg) and calcium (Ca).

Engineered carbon mineralization practices aim to optimize or enhance one or more of these rate-limiting factors. As discussed in detail in subsequent chapters, interventions range from simple and relatively inexpensive, such as finely grinding rocks to increase surface area, to much more complex and energy and cost intensive, such as heating the minerals to high temperatures to increase their reactivity and exposing them to higher concentrations of CO_2.

Box 2-1

ULTRAMAFIC AND MAFIC ROCKS

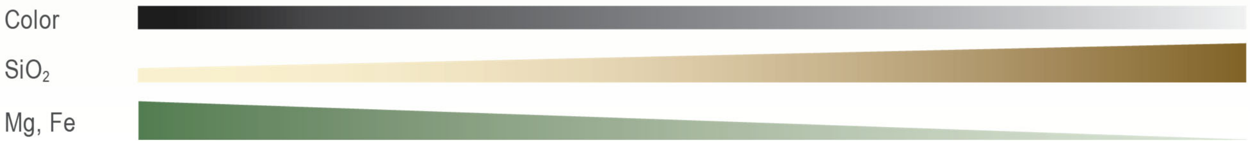
Rocks can be classified into four categories based on their chemical composition: ultramafic, mafic, intermediate and felsic. These categories form a spectrum, with ultramafic rocks at one end and felsic rocks at the other end. Ultramafic rocks have the highest proportions of magnesium (Mg) and iron (Fe) and lowest proportion of silica (SiO_2). Mafic rocks are next on the spectrum, with less Mg and Fe and more SiO_2 than ultramafic rocks, as well as more calcium (Ca).

The differences between rocks in each category are caused by geologic processes such as melting, eruption and crystallization. Ultramafic and mafic rocks are most suitable for carbon mineralization because they contain the highest proportions of Mg and Ca, which form stable carbonate minerals, such as magnesite ($MgCO_3$) and calcite ($CaCO_3$).

The most abundant ultramafic rocks on Earth are "peridotites," which are the dominant rock in Earth's upper mantle. They are most common in Oman, the United Arab Emirates, New Caledonia, Papua New Guinea and Albania. There are also substantial peridotite massifs in Japan and the western United States.

The Earth's oceanic crust is composed of a remarkably uniform 7-km-thick layer of mafic rocks. Rocks compositionally similar to the oceanic crust are common on land in many regions, including Japan, Hawaii, the northwest United States and Iceland.

	ULTRAMAFIC	MAFIC	INTERMEDIATE	FELSIC
Example rocks	Peridotite, Pyroxenite, Dunite	Basalt, Gabbro	Andesite, Diorite	Rhyolite, Granite
Major minerals	Olivine, pyroxene	Plagioclase feldspar, pyroxene, olivine	Plagioclase feldspar, amphibole or pyroxene	Potassium feldspar, quartz, plagioclase feldspar



Rocks most suitable for carbon mineralization are those that undergo rapid chemical weathering and release cations that readily form stable carbonate minerals, such as magnesium and calcium. (Carbonates containing other cations, such as sodium (Na) and potassium (K), can also form through chemical weathering, however such carbonates dissolve readily and are therefore not long-term sinks for CO_2.) Suitable rocks include two categories of igneous rocks known as mafic and ultramafic rocks, which include dunite, peridotite and basalt, and the metamorphosed version of the ultramafic rocks known as serpentinites. These rocks are composed of magnesium- and iron-rich and calcium-bearing silicate minerals, including olivine, pyroxenes and serpentine, and may also contain other reactive minerals, such as the hydroxide mineral brucite. The mineral wollastonite also reacts rapidly and is found in either rocks where silica and limestone are metamorphosed at high temperatures or in rocks known as carbonatites, which form from magmas rich in carbon. However, the global reserves of wollastonite are ~100 million tons, whereas there are hundreds of trillions of tons of peridotite, basalt and other mafic rocks within a few kilometers of the Earth's surface. Other rocks, minerals and alkaline industrial wastes may also be suitable, as discussed in more detail in subsequent chapters.

Ultramafic rocks suitable for carbon mineralization consist mainly of those from the Earth's mantle that are now exposed at the surface. As shown in Chapter 1, Figure 1, these rocks occur along current and former tectonic plate boundaries and areas of tectonic uplift and rift zones. Mafic rocks suitable for carbon mineralization consist primarily of basaltic lavas and their subsurface equivalents, gabbros. These rocks form the 7-km-thick igneous crust underlying the ocean basins and are abundant on land in flood basalt provinces (e.g., the Columbia River basalts), volcanic ocean islands (also known as "hotspots", e.g., Hawaii, Iceland), volcanic arcs above subduction zones (e.g., most of Japan, the Cascade volcanoes in the United States), and continental rift zones (e.g., the Rio Grande rift).

The various suitable rocks and their constituent minerals react at different rates. Brucite, wollastonite, fibrous serpentine minerals (e.g., chrysotile asbestos), olivine and basaltic glass are among the fastest reacting, while pyroxenes and feldspars are slower to react.[3] As noted above, the reaction rate depends on factors including temperature, partial pressure of CO_2 and pH. For a given combination of minerals and fluid compositions, the amount of time to achieve complete carbon mineralization can vary from hours to years, depending on the initial surface area and grain size.[3]

Some reactive rocks and minerals are abundant, whereas others are relatively scarce. Brucite typically makes up only a small fraction of ultramafic rocks—at most 10 percent by weight but typically much less. Wollastonite is also not geologically abundant, occurring in significant quantities in only a few locations globally. Conversely, olivine and serpentine are abundant, particularly in ultramafic rocks, such as peridotite. Mafic rocks are somewhat slower to react than ultramafic rocks because they contain higher proportions of slower reacting minerals. Also, they have a smaller CO_2 storage capacity than ultramafic rocks. However, mafic rocks are also about an order of magnitude more abundant at the Earth's surface than ultramafic rocks and so, overall, represent a larger possible CO_2 sink.

The total amount of CO_2 that can be removed using engineered carbon mineralization depends on which minerals are dissolving and which minerals are forming and, particularly, on the amount of magnesium and calcium ions contained in the dissolving minerals, as well as the ratio of CO_2 magnesium or calcium incorporated in the carbonate minerals that form. On average, approximately 0.4 tCO_2 can be sequestered for every ton of reactive rock.[4] More specifically, the amount of CO_2 that can be removed at any particular site or using any particular rock depends on site-specific mineralogy and geochemistry. Approximately 0.55 tCO_2 can be sequestered for every ton of typical ultramafic rock (mantle peridotite), and about one third of that amount can be sequestered for every ton of mafic rock.

Carbon mineralization can be engineered to achieve (1) CO_2 removal from air (CDR) or (2) permanent, inert, non-toxic storage. These goals are generally accomplished via one of three broad methodologies, as will be discussed in more depth in the chapters that follow:

1. *In situ*: CO_2-bearing aqueous fluids or H_2O-bearing dense CO_2 fluids under pressure ("damp supercritical CO_2," sc CO_2) are circulated underground through reactive rocks to achieve subsurface carbon mineralization. Carbon-depleted aqueous fluids can then be returned to the surface, either to draw down CO_2 from air or simply to be recycled in order to reduce water withdrawals and consumption.
2. Surficial: Captured or ambient CO_2 is reacted with crushed rock. This approach can be performed where the rocks occur (e.g., in mine tailings and alkaline industrial waste sites) or in more distal settings (e.g., as amendments to agricultural soil or as dispersed material along beaches).
3. *Ex situ*: Reactive rocks are transported to a source of CO_2, industrial facility or other location, where they are crushed and ground and then reacted with captured or ambient CO_2, often under high temperature and/or pressure conditions.

In addition to CO_2 removal from air and storage of CO_2 captured elsewhere, a set of hybrid methods can be envisaged. These methods start with gas enriched in CO_2 (flue gas or CO_2-rich gas produced via partial DAC). CO_2 from the enriched gas is then dissolved to form CO_2-enriched water at depth. Then, the CO_2-enriched water is circulated through reactive materials. Because CO_2 is more soluble in water than other gases that are abundant in air (e.g., oxygen, nitrogen) and because, in turn, carbon mineralization further "purifies" CO_2 in carbonate minerals thereby removing it from aqueous fluids, such hybrid methods achieve both CO_2 removal from air and permanent solid storage. This is discussed more fully in Chapter 3.

REFERENCES

1 John M Hayes & Jacob R Waldbauer. The carbon cycle and associated redox processes through time. *Philosophical Transactions of the Royal Society B: Biological Sciences* **361**, 931-950, doi:10.1098/rstb.2006.1840 (https://royalsocietypublishing.org/doi/abs/10.1098/rstb.2006.1840) (2006).

2 P. Ciais *et al. Carbon and Other Biogeochemical Cycles (in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change)*. ((eds. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley) Cambridge University Press; Cambridge, United Kingdom and New York, NY, USA, 2013).

3 National Academies of Sciences (Engineering and Medicine) (NASEM). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. (Washington, DC: The National Academies Press, 2019; https://doi.org/10.17226/25259).

4 Ian M. Power *et al.* Carbon Mineralization: From Natural Analogues to Engineered Systems. *Reviews in Mineralogy and Geochemistry* **77**, 305-360, doi:https://doi.org/10.2138/rmg.2013.77.9 (2013).

CHAPTER 3:

UNDERGROUND INJECTION

INTRODUCTION

When carbon dioxide (CO_2) is injected underground into certain types of rocks, the CO_2 reacts with those rocks to form solid, stable, non-toxic minerals that permanently remove the CO_2 from the atmosphere. This is known as *in situ* mineralization.

In situ mineralization requires the presence of subsurface rocks rich in magnesium and/or calcium, commonly termed "*mafic*" and "*ultramafic*" rocks. These are found in many places around the world. (See text box and map in Chapter 2.) The CO_2 is injected underground in fluids (either aqueous fluids containing dissolved CO_2 or CO_2 fluids at high pressure).

TYPES OF *IN SITU* MINERALIZATION

In situ mineralization can be divided into three broad categories: (1) CO_2 removal from air with mineral storage (CO_2 removal), (2) CO_2 capture from point sources with mineral storage (CO_2 storage) and (3) hybrid approaches. The key distinguishing feature of these different categories is whether mineralization itself is removing CO_2 from the atmosphere (removal and hybrid approaches) or whether CO_2 is being removed or captured using other technologies (storage).

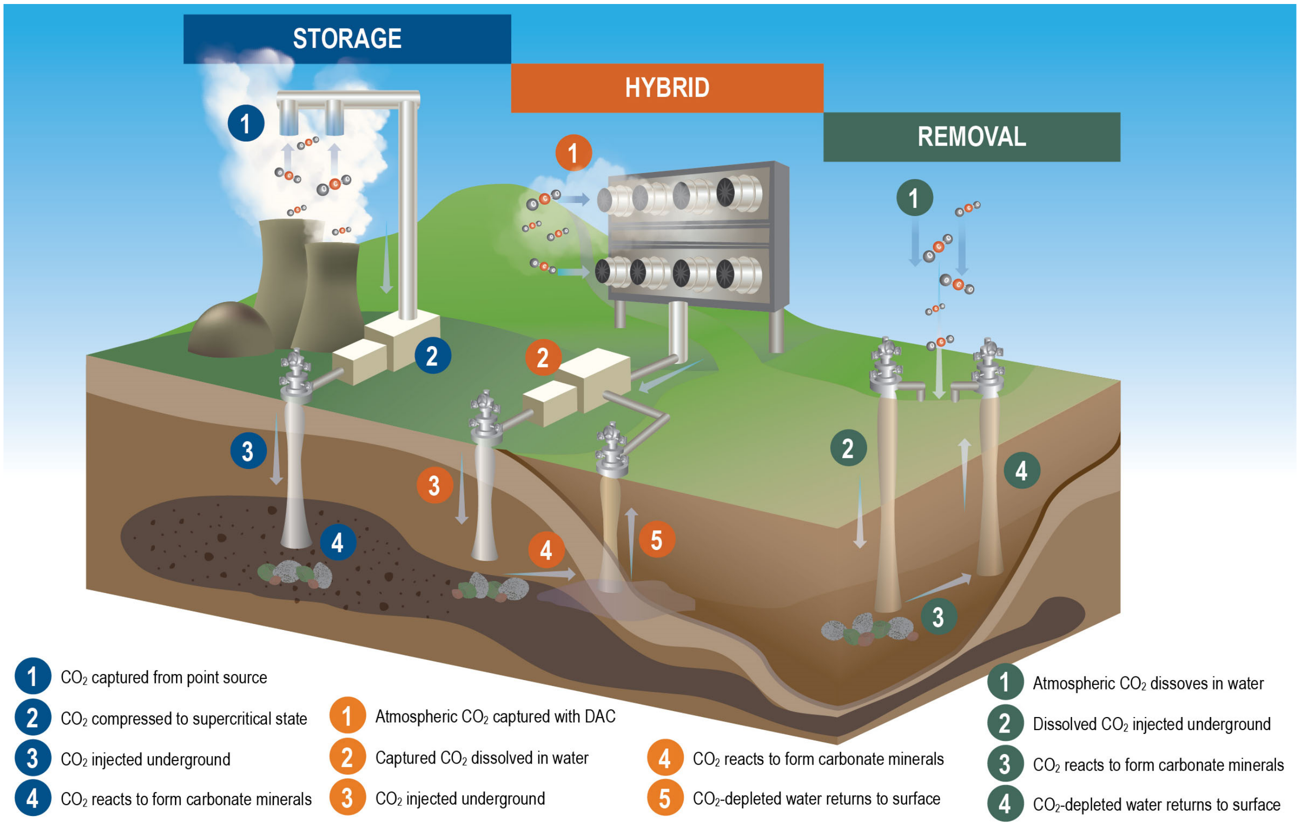


Figure 3.1. In Situ Mineralization.

1. CO_2 removal from air with mineral storage (CO_2 removal)

Water at the Earth's surface naturally contains dissolved CO_2 derived from the atmosphere. When this water circulates underground through ultramafic rocks, such as "peridotite," the CO_2 in the water reacts with minerals in the rock to form new carbonate minerals. When returned to the surface, the CO_2-depleted water then absorbs more atmospheric CO_2, and the process is repeated. This natural process can be replicated and accelerated to increase the rate of atmospheric carbon removal by drilling a series of wells to increase the rate of water circulation and CO_2 removal.[1] Because the amount of CO_2 removed is greater than any emissions associated with the process, negative emissions can be achieved.

Production and re-use of carbon-depleted water can reduce water withdrawal and consumption. That said, this method is water-intensive and might best be pursued where reactive rocks are present along coastlines or beneath the seafloor. Also, because the concentration of dissolved CO_2 in surface waters is low, compression or pumping of surface water is expensive per ton of CO_2 removed. Thus, thermal convection and natural groundwater flow are small but important drivers for CO_2 transport, limiting the flux of fluid down boreholes and the amount of CO_2 removed from air per borehole per year.

2. CO_2 captured from point sources with mineral storage (CO_2 storage)

CO_2 captured from point sources—such as coal or natural-gas power plants or industrial facilities that produce process emissions, such as cement and steel plants—can also be stored through *in situ* mineralization. Captured CO_2 is injected—as a CO_2-rich aqueous fluid or a dense CO_2 fluid at high pressure—into subsurface mafic or ultramafic rocks where it reacts to form carbonate minerals. In this case, *in situ* mineralization is a form of geologic carbon storage, not a negative emissions technology in and of itself, and the associated emissions reductions are considered avoided emissions rather than negative emissions.

To date, two different methods have been used for mineral storage of CO_2 captured from point sources: injection of dense, supercritical CO_2 fluid and injection of CO_2 dissolved in water.

- 2a. Supercritical CO_2: Using this method, captured CO_2 is compressed, reaching a density similar to that of water, and then injected underground. For mineralization to occur, either a small amount of water must be dissolved into the CO_2 fluid or the formation into which the CO_2 is injected must contain water. Supercritical CO_2 is more buoyant than water at practically accessible depths, so it is crucial that the storage formation is capped by an impermeable caprock formation that traps the CO_2 underground until it mineralizes, known as "structural trapping."
- 2b. Dissolved CO_2: Using this method, captured CO_2 is dissolved in water and then injected underground. The dissolved CO_2 is no longer buoyant, providing additional storage security—known as "solution trapping"—prior to mineralization. This method allows storage in formations that do not have an impermeable caprock. The amount of water required to dissolve a given amount of CO_2 depends on factors including temperature and pressure. For example, at the CarbFix Phase I project in Iceland, compressed CO_2 was bubbled into descending water in a borehole at a depth of ~ 345 m, corresponding to a water pressure of

about 35 atmospheres. At this pressure, approximately 25 tons of water were used to dissolve 1 tCO_2. Because the water at this site flows freely downward, only the CO_2 required compression in this method (to about 27 bars at the surface), reducing costs substantially. As in the CO_2 removal methods discussed above, the water used for solution trapping can be brought back to the surface and re-used.

3. Hybrid approaches

In situ mineralization can also be paired with other carbon dioxide removal (CDR) technologies, such as direct air capture (DAC) or biomass carbon removal and storage (BiCRS), to generate negative emissions. The use of nearly pure CO_2 gas or CO_2 fluid requires prior production of purified CO_2 via DAC or capture from point sources. However, the purity of CO_2-bearing gas produced by DAC methods can vary. From a theoretical perspective, the higher the purity of CO_2, the more energy is required for DAC. Thus, for example, enrichment of air to 10 mol% CO_2 uses about one third of the energy required to enrich air to 95 mol% CO_2.[2]

As a result, hybrid methods are possible. These methods start with CO_2-enriched gas (flue gas or CO_2-rich gas produced via partial DAC). CO_2 from the enriched gas is then dissolved to form CO_2-enriched water at depth. Then, the CO_2-enriched water is circulated through reactive materials. Because CO_2 is more soluble in water than other gases that are abundant in air (e.g., oxygen, nitrogen) and because carbon mineralization further “purifies” CO_2 in carbonate minerals thereby removing it from aqueous fluids, such hybrid methods achieve CO_2 capture (from air or flue gas), as well as permanent solid storage. Such hybrid methods can achieve greater CO_2 removal per borehole than CO_2 removal alone.[1] Storing concentrated CO_2 captured from DAC or BiCRS in mafic or ultramafic rocks could also expand the geographic range for these CDR technologies to places where sedimentary geologic storage is not available.

LOCATION OF APPROPRIATE ROCKS AND NATURAL ANALOGS

Ultramafic rocks suitable for CO_2 removal from air with mineral storage consist mainly of mantle peridotite, magnesium-rich rocks from the Earth’s interior that are exposed at the Earth’s surface by uplift and erosion. As shown in the map in Figure 1.1, these rocks occur along current and former tectonic plate boundaries and areas of uplift or extension. Tens to hundreds of trillions of tons of peridotite are located within 3 km of the Earth’s surface, with several particularly promising locations, including Oman, the United Arab Emirates, Papua New Guinea, New Caledonia, the east coast of the Adriatic Sea and the western Mediterranean.[3]

Mafic rocks suitable for CO_2 storage consist primarily of basalts formed through volcanism associated with tectonic plate boundaries (convergent and divergent) and mantle hot spots. The majority of the ocean floor is made of basalt, and enormous volcanic deposits known as “flood basalts” occur on many continents, including at the Columbia River Basalt Group in the United States, the Deccan Traps in India and the Siberian Traps in Russia.[4] Volcanic oceanic islands, such as Iceland and Hawaii, are also primarily composed of basalt.

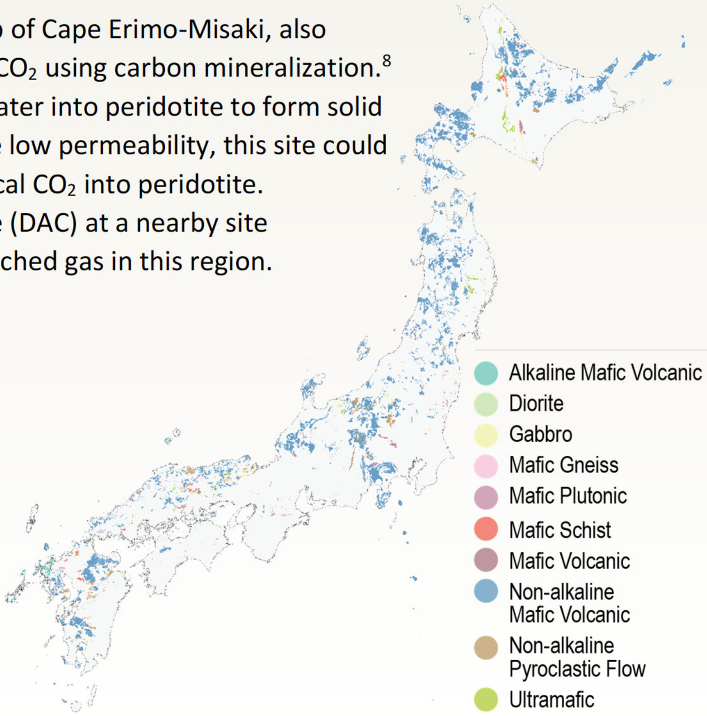
Natural carbonation of ultramafic rocks occurs in various locations around the world. The best-studied example is the Samail ophiolite in Oman.[5] The Samail ophiolite is a block of oceanic crust and underlying mantle peridotite that is now exposed at the Earth's surface due to tectonic processes, faulting and erosion. The mantle peridotite has been partially altered through interaction with heat and water to serpentinite, and both the peridotite and the serpentinite show abundant evidence of carbon mineralization. Approximately 10^4–10^5 tons of atmospheric CO_2 are removed from air and sequestered each year through carbon mineralization of mantle peridotite in Oman.[6] This result indicates the potential for mineralization to draw down significant quantities of atmospheric CO_2.

Box 3-1

IN SITU MINERALIZATION OPPORTUNITIES IN JAPAN

Japan is ideally suited for in situ (subsurface) carbon mineralization, both for CO_2 removal from air and for CO_2 storage. The many active volcanoes on and near the Japanese coast (including in shallow submarine locations) form young, glassy basalts, which are ideal reactants for CO_2. Many locations along the Japanese coast offer excellent opportunities for the "solution trapping" method of storing CO_2 via mineralization. These sites are visible at a regional scale as coastal "non-alkaline mafic volcanic rocks" in the geological maps compiled by Myers and Nakagaki, 2020.[7]

South-central Hokkaido, near the southern tip of Cape Erimo-Misaki, also presents significant opportunities for storing CO_2 using carbon mineralization.[8] This site is ideal for storing CO_2 by injecting water into peridotite to form solid carbonates. If the overlying crustal rocks have low permeability, this site could also be suitable site for injection of supercritical CO_2 into peridotite. Because this area is remote, direct air capture (DAC) at a nearby site might be the most suitable source of CO_2-enriched gas in this region.



CURRENT PROJECTS

To date, two projects have demonstrated *in situ* mineralization of CO_2 in the field: the Wallula pilot project in Washington State, US and the CarbFix pilot (I) and industrial (II) projects in Iceland.

1. Wallula

The Wallula project in Washington State was conducted by the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to test the feasibility of permanently and safely sequestering CO_2 in basalt formations. The project injected approximately 1000 metric tons of damp supercritical CO_2 into two permeable horizons in the Columbia River Basalt Group at 830–890-m depth over 3 weeks in 2013. In the two years following injection, analysis of periodic fluid samples, geophysical data and sidewall cores all showed that new carbonate minerals had formed as a result of injecting CO_2. Unmineralized CO_2 remained beneath the caprock at the top of the injection zone, indicating that not all of the CO_2 had mineralized.[9,10] Instead, geophysical data suggest that approximately 60% of the injected CO_2 was sequestered via mineralization within two years. The fate of the remaining CO_2 is unclear, but no leakage has been detected. Carbonate minerals that formed as a result of the experiment occupy only ~ 4% of the available reservoir pore space, so the remaining storage potential is very large.[11]

2. CarbFix

The CarbFix project was conceived as a method to safely and permanently capture CO_2 and H_2S from emissions sources and store it as rock in the subsurface by imitating and accelerating the natural process of carbon mineralization. The CarbFix I pilot project injected 175 tons of CO_2 from January to March 2012 and 73 tons of 75% CO_2-25% H_2S gas mixture (non-condensable gases from the Hellisheiði geothermal plant) from June to August 2012. Gases were injected into descending water in a borehole as described above, forming CO_2-rich aqueous fluids for solution trapping. Tracer studies showed that 95% of injected CO_2 was mineralized in <2 years.[12,13] These encouraging results led to upscaling. Larger-scale operations began in 2014, simultaneously capturing CO_2 and H_2S from two of six high-pressure turbines at the Hellisheiði geothermal plant, with plans to eventually capture virtually all emissions. To date a total of approximately 70,000 metric tons of CO_2 have been injected as part of the CarbFix industrial project, and the project is still operational. In this later, larger-scale process, more than 60% of injected CO_2 is mineralized.[14]

CarbFix has also partnered with the Swiss DAC company, Climeworks. Together, they built a small-scale pilot DAC facility called Arctic Fox as part of CarbFix II. Following on the success of that project, the two companies built a combined DAC–carbon mineralization project called Orca, which commenced operations in 2021, with a capacity to remove and store 4000 tCO_2 per year.[15]

UNCERTAINTIES AND BARRIERS TO SCALE-UP

The Wallula and CarbFix projects demonstrated the viability of secure CO_2 storage and rapid mineralization in basalt. Additional and larger-scale field projects are the next logical step to quantify storage capability and capacity in other regions and to demonstrate that the technology can accommodate storage volumes that meaningfully contribute to climate mitigation. Such pilot projects should build on the lessons learned from existing projects. Key research questions for *in situ* mineralization include the topics discussed below.

1. Monitoring

Unlike surficial and *ex situ* mineralization, subsurface carbon mineralization processes cannot be observed directly, and collection of physical samples of mineralization products is more complicated and costly. Reliable, rapid and cost-effective indirect methods for characterizing the rate and extent of carbon mineralization are needed. A variety of measurement, monitoring and modeling techniques have been deployed at Wallula and CarbFix to assess mineralization reactions and efficiency.[9-14,16-19] Additional field projects can help constrain which techniques will be most successful for large-scale deployment and can contribute to development of strategies to optimize mineralization efficiency under real-world conditions.

2. Negative and positive feedbacks

Passivation of the mineralization reaction over time is a potential issue for *in situ* mineralization projects. The three primary causes of this passivation would be (1) nearly complete consumption of rapidly reacting minerals, leaving only less reactive minerals behind; (2) coating of reactive surfaces with non-reactive minerals and (3) clogging of pore space by newly precipitated minerals. Temperature and volume changes occurring during mineralization could lead to thermal- and/or mineralization reaction–driven microfracturing of the host rock, which could help prevent loss of reactivity by opening cracks that expose fresh rock surfaces and help maintain permeability.[20-22] Dissolution of minerals in low-pH, CO_2-rich aqueous fluids near the site of injection could also enhance permeability, forming high porosity channels of focused fluid flow via the “reactive infiltration instability”).[23] Additional research is needed to understand the controls on the negative-feedback passivation and clogging and positive-feedback cracking and channeling mechanisms.[5] Co-injection of different fluids at adjacent boreholes could potentially be used to localize mineral precipitation, reaction-driven cracking and formation of dissolution channels.[24]

3. Environmental and human health and safety impacts

Two primary environmental and human health and safety concerns associated with underground storage of CO_2 and other fluids include the following:

a. *Potential impacts to drinking water aquifers.* Supercritical CO_2 is buoyant in the subsurface and can migrate vertically if an open pathway is present, such as a transmissive fault, a newly formed hydraulic fracture, an acid-induced dissolution channel (also known as a “wormhole”) or an improperly constructed, maintained or abandoned wellbore. Such leakage could potentially allow injected CO_2-containing solutes derived from the host rock to impact shallow groundwater or surface water.

b. *Injection-induced earthquakes.* Scientist have known for decades that injecting fluids underground can cause earthquakes by creating increased pore fluid pressure and/or changes in rock volume that allow faults to slip. As of 2013, no induced earthquakes large enough to be felt at the surface have been documented as resulting from CO_2 storage.[25]

Both issues have been well-studied in sedimentary rocks through decades of experience with underground injection. Best practices and lessons learned from sedimentary settings can be applied to CO_2 storage in basalts and other mafic and ultramafic rocks. Although no impacts from CO_2 storage have been documented to date, the risks scale as the number and size of projects increase. Methods and practices to monitor for such impacts can be integrated into *in situ* field projects to help constrain the specific risks of carbon mineralization and to develop methods to mitigate these risks.

4. Reaction kinetics, rock mechanics and site identification

Additional basic research on topics such as reaction kinetics and rock mechanics of ultramafic rocks combined with small-scale field trials (similar in scale to Wallula or CarbFix I) to characterize the geology, rock properties and mineralization rates of various potential carbon-removal sites are crucial to scaling CO_2 removal from air with mineral storage.[1,5]

REFERENCES

1 Peter B. Kelemen *et al.* Engineered carbon mineralization in ultramafic rocks for CO2 removal from air: Review and new insights. *Chem. Geol.* **550**, 119628, doi:https://doi.org/10.1016/j.chemgeo.2020.119628 (2020).

2 Jennifer Wilcox, Peter C. Psarras & Simona Liguori. Assessment of reasonable opportunities for direct air capture. *Environ. Res. Lett.* **12**, 065001, doi:10.1088/1748-9326/aa6de5 (2017).

3 Peter B. Kelemen *et al.* Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO2 Capture and Storage. *Annu. Rev. Earth Planet. Sci.* **39**, 545-576, doi:10.1146/annurev-earth-092010-152509 (https://www.annualreviews.org/doi/abs/10.1146/annurev-earth-092010-152509) (2011).

4 B. Peter McGrail *et al.* Potential for carbon dioxide sequestration in flood basalts. *Journal of Geophysical Research: Solid Earth* **111**, doi:https://doi.org/10.1029/2005JB004169 (2006).

5 National Academies of Sciences (Engineering and Medicine) (NASEM). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. (Washington, DC: The National Academies Press, 2019; https://doi.org/10.17226/25259).

6 Peter B. Kelemen & Jürg Matter. In situ carbonation of peridotite for CO(2) storage. *Proc Natl Acad Sci U S A* **105**, 17295-17300, doi:10.1073/pnas.0805794105 (2008).

7 Corey Myers & Takao Nakagaki. Direct mineralization of atmospheric CO2 using natural rocks in Japan. *Environ. Res. Lett.* **15**, 124018, doi:10.1088/1748-9326/abc217 (2020).

8 Hiroshi Yamamoto *et al.* Subhorizontal tectonic framework of the Horoman peridotite complex and enveloping crustal rocks, south-central Hokkaido, Japan. *Island Arc* **19**, 458-469, doi:https://doi.org/10.1111/j.1440-1738.2010.00714.x (2010).

9 B. P. McGrail *et al.* Wallula Basalt Pilot Demonstration Project: Post-injection Results and Conclusions. *Energy Procedia* **114**, 5783-5790, doi:https://doi.org/10.1016/j.egypro.2017.03.1716 (2017).

10 B. P. McGrail, F. A. Spane, E. C. Sullivan, D. H. Bacon & G. Hund. The Wallula basalt sequestration pilot project. *Energy Procedia* **4**, 5653-5660, doi:https://doi.org/10.1016/j.egypro.2011.02.557 (2011).

11 Signe K. White *et al.* Quantification of CO2 Mineralization at the Wallula Basalt Pilot Project. *Environ. Sci. Technol.* **54**, 14609-14616, doi:10.1021/acs.est.0c05142 (2020).

12 Juerg M. Matter *et al.* Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science* **352**, 1312-1314, doi:10.1126/science.aad8132 (2016).

13 Sandra Ó Snæbjörnsdóttir *et al.* The chemistry and saturation states of subsurface fluids during the in situ mineralisation of CO2 and H2S at the CarbFix site in SW-Iceland. *Int. J. Greenh. Gas Control* **58**, 87-102, doi:https://doi.org/10.1016/j.ijggc.2017.01.007 (2017).

14 Ingvi Gunnarsson *et al.* The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. *Int. J. Greenh. Gas Control* **79**, 117-126, doi:https://doi.org/10.1016/j.ijggc.2018.08.014 (2018).

15 CarbFix. *Our Story*, <https://www.carbfix.com/our-story> (Accessed September 2021).

16 Edda S. P. Aradóttir, Eric Sonnenthal, GrÌmur Bjˆrnsson & Hannes JÛnsson. Multidimensional reactive transport modeling of CO2 mineral sequestration in basalts at the Hellisheidi geothermal field, Iceland. *Int. J. Greenh. Gas Control* **9**, 24-40 (2012).

17 Eric H. Oelkers *et al.* Using stable Mg isotope signatures to assess the fate of magnesium during the in situ mineralisation of CO2 and H2S at the CarbFix site in SW-Iceland. *Geochimica et Cosmochimica Acta* **245**, 542-555, doi:https://doi.org/10.1016/j.gca.2018.11.011 (2019).

18 Sandra Ó Snæbjörnsdóttir, Sigurdur R. Gislason, Iwona M. Galeczka & Eric H. Oelkers. Reaction path modelling of in-situ mineralisation of CO2 at the CarbFix site at Hellisheidi, SW-Iceland. *Geochimica et Cosmochimica Acta* **220**, 348-366, doi:https://doi.org/10.1016/j.gca.2017.09.053 (2018).

19 Philip A. E. Pogge von Strandmann *et al.* Rapid CO2 mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes. *Nat. Commun.* **10**, 1983, doi:10.1038/s41467-019-10003-8 (2019).

20 John F. Rudge, Peter B. Kelemen & Marc Spiegelman. A simple model of reaction-induced cracking applied to serpentinization and carbonation of peridotite. *Earth and Planetary Science Letters* **291**, 215-227, doi:https://doi.org/10.1016/j.epsl.2010.01.016 (2010).

21 Peter B. Kelemen & Greg Hirth. Reaction-driven cracking during retrograde metamorphism: Olivine hydration and carbonation. *Earth and Planetary Science Letters* **345-348**, 81-89, doi:https://doi.org/10.1016/j.epsl.2012.06.018 (2012).

22 Owen Evans, Marc Spiegelman & Peter B. Kelemen. Phase-Field Modeling of Reaction-Driven Cracking: Determining Conditions for Extensive Olivine Serpentinization. *Journal of Geophysical Research: Solid Earth* **125**, e2019JB018614, doi:https://doi.org/10.1029/2019JB018614 (2020).

23 E. Aharonov, M. Spiegelman and P.B. Kelemen. Three-dimensional flow and reaction in porous media: Implications for the Earth's mantle and for sedimentary basins. *Journal of Geophysical Research* **102 (B7)**, 14821-14833 (1997; http://science.whoi.edu/labs/mclean210/kelemen/pages/Aharonov%20et%20al%20JGR%2097.pdf).

24 Peter B. Kelemen, Heather Savage, Theodore A. Koczynski & Columbia University. Methods and systems for causing reaction driven cracking in subsurface rock formations. US Patents 20150129209A1 & 9657559B2.

25 National Research Council. *Induced Seismicity Potential in Energy Technologies*. (The National Academies Press, 2013; https://doi.org/10.17226/13355).

CHAPTER 4:

ENHANCED ROCK WEATHERING

Introduction and fundamentals

"Weathering" is the breakdown or dissolution of rocks at the Earth's surface and has been an important regulator of atmospheric carbon dioxide (CO_2) over geologic time.[1,2] This weathering process involves the reaction of CO_2 in rainwater with rocks, dissolving out calcium and magnesium. These elements and dissolved CO_2 are transported in surface and ground waters to the oceans, where "carbonate minerals" may form, trapping the CO_2 in a solid and permanently removing it from the atmosphere.

This form of carbon mineralization occurs at vast spatial and temporal scales. The current level of CO_2 removal through natural silicate weathering is approximately 0.3 Gt of atmospheric CO_2 per year.[1,3]

Enhanced rock weathering (ERW) aims to dramatically accelerate this natural CO_2 removal process. This approach involves applying rock powder with the ability to react with CO_2 over large land areas, along coasts, or in the oceans.[4] ERW raises the alkalinity of soils and waters, thereby drawing down CO_2 from the atmosphere and storing it as a dissolved phase in water and solid carbonate mineral.[3,5,6]

ERW can have positive environmental impacts beyond removing CO_2 from the atmosphere, including neutralizing acidification. CO_2 emissions cause acidification in a number of ecosystems, including the oceans, since CO_2 dissolved in water produces weak carbonic acid (H_2CO_3). Spreading alkaline rock powder neutralizes this acidity, similar to the use of lime for neutralizing acid rain caused by sulfur dioxide (SO_2) emissions.

Suitable rock types for ERW include mafic and ultramafic rocks such as basalt, dunite and peridotite. These rocks contain alkaline minerals such as olivine, a magnesium silicate.[7-12] The key selection criterion is that the rock

Figure 4.1. Enhanced Rock Weathering.

must contain an abundance of alkaline Mg- and Ca-bearing minerals that readily weather at the Earth's surface, thus providing relatively fast CO_2 removal rates. Many other rocks and minerals can be utilized for ERW and carbon mineralization, including serpentine, wollastonite, brucite and kimberlite.[13-16] Ultramafic mine wastes have been shown to sequester atmospheric CO_2 through surface weathering[17] and may be suitable for ERW. Furthermore, numerous industrial wastes, including blast furnace and steel slag, cement kiln dust, and waste concrete, are reactive with CO_2 and could be used as an ERW feedstock instead of natural rock.[18] In addition to properties of the rock powder (e.g., mineralogy and grain size), a dispersal site's climate and environmental conditions (e.g., soil properties) will significantly influence the rates of CO_2 removal. Proposed sites for ERW include arable lands,[7] oceans,[11] coastal areas[19] and degraded lands, such as forests that have been impacted by acid rain.[20]

For the abundant silicate minerals that offer the greatest capacities for CO_2 sequestration, slow dissolution rates are expected to be the main rate-limiting factor of ERW and carbon mineralization.[21] The dissolution rates of minerals can vary by orders of magnitude. Selecting rock with reactive minerals is therefore paramount. Finer grain sizes with higher surface areas can help minimize this limitation.[22]

ERW is an attractive option for carbon removal for several reasons. First, ERW is a low-tech process that mimics natural carbon mineralization. Second, ERW offers essentially unlimited CO_2 sequestration capacity. Third, ERW utilizes existing technology in industries such as mining and agriculture. Finally, ERW does not compete with other land uses (in contrast with some other negative emissions technologies).

ERW has several parallels with the direct air capture (DAC) technologies that Climeworks and Carbon Engineering are developing.[23] These technologies use alkaline sorbents that absorb CO_2 from the atmosphere. Alkaline powdered rock also "absorbs" CO_2 through weathering and carbonation. Although alkaline powdered rocks are less reactive than DAC sorbents, these rocks are abundant on Earth and inexpensive to quarry and grind without special engineering or technologies. Another important distinction between these approaches is that ERW accomplishes both CO_2 capture and storage, whereas DAC technologies only capture CO_2, requiring subsequent storage or use via other processes.

Capacities and co-benefits

ERW using natural bedrock has an essentially unlimited capacity to sequester CO_2. For instance, the potential for CO_2 removal using dunite and basalt powders applied over agricultural lands could be 95 and 4.9 $GtCO_2$ per year, respectively,[22] assuming use of all the vast agricultural lands in warm (5.1×10^6 km^2) and temperate (2.8×10^6 km^2) regions. Consistent with this approximation, another estimate suggests that 0.5–2.0 $GtCO_2$ per year could be removed from the atmosphere if dispersed basalt powder were applied to 10–50% of global cropland.[24] Similarly, dispersal of basalt dust over all of the Earth's hinterland (55 million km^2) could remove 2.5 $GtCO_2$ per year over 50 years, including the estimated contribution of additional biomass accumulation.[25] In coastal environments, a one-time application of 26 Gt of olivine powder (12 km^3) along beaches is estimated to have the potential to remove up to 0.3 GtCO_2 per year over 30 years.[26] As such, the potential for sequestering CO_2 through ERW is immense if scaled through expanded mining and wide dispersal over large areas.

ERW has several co-benefits that may be initial drivers for its deployment. Applying powdered rock releases nutrients (such as potassium and phosphorous), stabilizes organic matter and improves water retention, all of which enhance soil fertility[25] and buffer soil acidity. Thus, ERW may benefit areas historically impacted by acid rain. For example, when applied to an impacted forested watershed, wollastonite powder neutralized acidity, replenished nutrients and led to sequestration of 8.5–11.5 tCO_2 per hectare.[20] For these reasons, agricultural fields are a prime dispersal site, given their vast land areas and the widely used technology for applying fertilizers. Moreover, applying rock powder to agricultural fields is an existing practice. For example, pulverized limestone is used to reduce soil acidity. In addition to improved crop yields, increasing soil alkalinity also prevents nitrous oxide (N_2O) and methane (CH_4) loss, further reducing greenhouse gas (GHG) emissions.[24,27] Countries with relatively warm climates and productive agriculture industries, such as the United States, Brazil, China and India, have the greatest potential to capitalize on ERW in agricultural soils.[24]

Current status of field pilots, research needs and costs

Several field pilots have or will soon be initiated to evaluate ERW efficacy, CO_2 removal rates and potential environmental co-benefits and impacts. Carbon Drawdown[28] aims to test the integration of ERW with other negative emissions technologies, using mixtures of basalt and olivine combined with biochar in agricultural fields in Germany and Greece. Carbon Removed[29] and greenSand aim to advance the use of olivine for several ERW applications. Project Vesta[30] examines the application of olivine to coastal areas, thereby trapping CO_2 as a soluble phase and directly addressing ocean acidification. OceanNETs[31] aims to advance ocean alkalinization and other negative emissions technologies, including blue carbon management. In yet another approach, the Future Forest Company[32] is carrying out large-scale ERW trials in forested areas to better define co-benefits, potential negative impacts and costs. The Leverhulme Centre for Climate Change Mitigation[33] has launched several field trials to answer questions related to weathering of basalt dust in agricultural soils and how this may increase food and bioenergy crop production.[24] In addition, Carleton College initiated an agricultural pilot to address the lack of data on ERW at the field scale. Similarly, other field trials have investigated the use of wollastonite powder on agricultural fields for its dual purposes of enhancing soil fertility and CO_2 removal.[13] The findings of these larger and long-term pilots will enable researchers to address uncertainties and research needs for advancing the technology readiness level (TRL) of ERW.

Chief among these needs are methodologies for determining CO_2 removal rates, which depend on rock properties (e.g., mineralogy), dosages (mass applied per area), and environmental conditions of the dispersal site. Although ERW is technologically simple compared to DAC, carbon accounting is more challenging with ERW due to its slow CO_2 removal rates and storage of CO_2 as either a soluble or solid phase. Furthermore, measuring spatially variable increases in soil carbon content against a spatially and temporally variable background provides additional challenges, as does the behavior of open-system reservoirs (e.g., removal of carbon in crops, crop residues and weeds and removal of dissolved CO_2 from soils in groundwater and surface runoff). Improving and developing assessment tools to verify carbon sequestration by ERW will require specific monitoring programs to track carbon or proxies to monitor ERW. Furthermore, verification tools are needed to account for the carbon stored as a soluble phase and exported into rivers and oceans, which is likely to be challenging to track.

Assessing environmental risk to soils, waters, air and ecosystems is important in deploying ERW. Although alkaline rocks contain nutrients, they may also contain metals that can be toxic if accumulated in soils and converted into bioactive compounds over time. Nickel and chromium are of the most concern. For example, accumulation of nickel in soils, leached from olivine-rich feedstock, may be detrimental to local ecosystems; although the levels observed so far are unlikely to cause harmful effects.[26,34] The amount of metal-loading will depend on the rock powder, dosage and application frequency. Dust may also be an issue to air quality during or after applying rock powder. Again, field pilots are necessary to address these concerns and uncertainties and to gain public acceptance.

The response and role of microbial communities in soils where rock powder is being applied also require further exploration. Soil microbes may accelerate mineral weathering by producing acids and chelating agents and by facilitating chemical reactions.[35] Soil microbes may also slow mineral dissolution rates by passivating surfaces.[10] In addition, plant processes may affect mineral weathering. All these issues will be specific to the soil environment of the application site and, thus, may be highly variable. Further research is also needed on the interaction between inorganic and organic carbon cycling in soils and on the potential impact of ERW on other factors affecting soil carbon storage, such as crop rotation, low or no-till practices, and retention of crop residues.

As part of field pilots, mine-to-field life-cycle analyses will improve estimates of costs and additional GHG emissions, particularly those from mining and transporting rock. For cropland areas, assessments to date suggest that ERW may cost approximately 60 $\$/tCO_2$ for dunite and 200 $\$/tCO_2$ for basalt for cropland areas.[22] Most costs are incurred through mining and crushing, followed by those for transport, estimated at 0.05 $/km/t of rock, and distribution, estimated at 12–14 $/t of rock. Dispersal of basalt dust in areas besides croplands will likely be more expensive due to increased application costs. Estimates range from 100–500 $\$/tCO_2$.[1] Mining rock in large masses (megatonnes per year per site) and minimizing transportation distances between sources and dispersal sites are essential to lowering costs.

Moving toward implementation

Widespread deployment of ERW will require an enormous increase in mining and dispersal over vast areas, as well as accurately measuring and verifying CO_2 storage. In addition to acting as a supplier of feedstock, the mining industry can assist in identifying and evaluating suitable rocks for ERW and ultimately mining these rocks to sell as a product. An ideal scenario would establish a local or regional network of ERW sites near mines or quarries with suitable rock.

Testing protocols for evaluating the suitability and reactivity of powdered rocks for ERW must also be available.[15] A process of approving the safe and effective use of powdered rocks is also required. Ensuring and demonstrating little to no environmental impact is critical to increasing public acceptance of the technology.[36] Regulations for application will also be needed. These will vary depending on the current land use of a given site (e.g., agricultural or disturbed lands) and may relate to existing environmental protection laws and restrictions for using solid wastes.[37] Furthermore, ERW and carbon mineralization are not included in many existing carbon accounting schemes (e.g., California LCFS, 45Q). Doing so would raise the profile of ERW as an economically viable negative emissions technology.

Addressing scientific uncertainties through field trials, evaluating practical issues including costs through life cycle analyses, and engaging with industry and government are crucial to advancing ERW as a viable negative emissions technology that can achieve meaningful CO_2 removal at a global scale.

Photograph is from an application of metabasalt powder (~2240 kg/hectare) to a test site of canola stubble near Wilcox, Saskatchewan, Canada (Courtesy of Ryan MT Brophy, V6 Agronomy Inc.).

REFERENCES

1 Nils Moosdorf, Phil Renforth & Jens Hartmann. Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering. *Environ. Sci. Technol.* **48**, 4809-4816, doi:https://doi.org/10.1021/es4052022 (2014).

2 Donald E. Penman, Jeremy K. Caves Rugenstein, Daniel E. Ibarra & Matthew J. Winnick. Silicate weathering as a feedback and forcing in Earth's climate and carbon cycle. *Earth-Sci. Rev.* **209**, 103298, doi:https://doi.org/10.1016/j.earscirev.2020.103298 (2020).

3 Jens Hartmann *et al.* Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* **51**, 113-149, doi:https://doi.org/10.1002/rog.20004 (2013).

4 The Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5°C - An IPCC Special Report*. (eds. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al., 2018 (https://www.ipcc.ch/sr15/)).

5 H. D. Holland, B. Lazar & M. McCaffrey. Evolution of the atmosphere and oceans. *Nature* **320**, 27-33, doi:10.1038/320027a0 (https://www.nature.com/articles/320027a0) (1986).

6 Lee R. Kump, Susan L. Brantley & Michael A. Arthur. Chemical Weathering, Atmospheric CO2, and Climate. *Annu. Rev. Earth Planet. Sci.* **28**, 611-667, doi:10.1146/annurev.earth.28.1.611 (https://www.annualreviews.org/doi/abs/10.1146/annurev.earth.28.1.611) (2000).

7 David J. Beerling *et al.* Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* **4**, 138-147, doi:10.1038/s41477-018-0108-y (2018).

8 Peter B. Kelemen *et al.* Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO2 Capture and Storage. *Annu. Rev. Earth Planet. Sci.* **39**, 545-576, doi:10.1146/annurev-earth-092010-152509 (https://www.annualreviews.org/doi/abs/10.1146/annurev-earth-092010-152509) (2011).

9 Filip J. R. Meysman & Francesc Montserrat. Negative CO2 emissions via enhanced silicate weathering in coastal environments. *Biol. Lett.* **13**, 20160905, doi:https://doi.org/10.1098/rsbl.2016.0905 (2017).

10 Eric H. Oelkers, Julien Declercq, Giuseppe D. Saldi, Sigurdur R. Gislason & Jacques Schott. Olivine dissolution rates: A critical review. *Chem. Geol.* **500**, 1-19, doi:https://doi.org/10.1016/j.chemgeo.2018.10.008 (2018).

11 Ioannis Rigopoulos *et al.* Carbon sequestration via enhanced weathering of peridotites and basalts in seawater. *Appl. Geochem.* **91**, 197-207, doi:https://doi.org/10.1016/j.apgeochem.2017.11.001 (2018).

12 Lyla L. Taylor *et al.* Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Chang.* **6**, 402-406, doi:https://doi.org/10.1038/nclimate2882 (2016).

13 Fatima Haque, Rafael M. Santos & Yi Wai Chiang. CO2 sequestration by wollastonite-amended agricultural soils – An Ontario field study. *Int. J. Greenh. Gas Control* **97**, 103017, doi:https://doi.org/10.1016/j.ijggc.2020.103017 (2020).

14 Anna L. Harrison, Ian M. Power & Gregory M. Dipple. Accelerated Carbonation of Brucite in Mine Tailings for Carbon Sequestration. *Environ. Sci. Technol.* **47**, 126-134, doi:10.1021/es3012854 (https://pubs.acs.org/doi/10.1021/es3012854) (2013).

15 Carlos Paulo *et al.* Evaluating feedstocks for carbon dioxide removal by enhanced rock weathering and CO2 mineralization. *Appl. Geochem.* **129**, 104955, doi:https://doi.org/10.1016/j.apgeochem.2021.104955 (2021).

16 James G. M. Thom, Gregory M. Dipple, Ian M. Power & Anna L. Harrison. Chrysotile dissolution rates: Implications for carbon sequestration. *Appl. Geochem.* **35**, 244-254, doi:https://doi.org/10.1016/j.apgeochem.2013.04.016 (2013).

17 Siobhan A. Wilson *et al.* Offsetting of CO2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining. *Int. J. Greenh. Gas Control* **25**, 121-140, doi:https://doi.org/10.1016/j.ijggc.2014.04.002 (2014).

18 Phil Renforth. The negative emission potential of alkaline materials. *Nat. Commun.* **10**, 1401, doi:10.1038/s41467-019-09475-5 (2019).

19 Suzanne J. T. Hangx & Christopher J. Spiers. Coastal spreading of olivine to control atmospheric CO2 concentrations: A critical analysis of viability. *Int. J. Greenh. Gas Control* **3**, 757-767, doi:https://doi.org/10.1016/j.ijggc.2009.07.001 (2009).

20 L. L. Taylor *et al.* Increased carbon capture by a silicate-treated forested watershed affected by acid deposition. *Biogeosciences* **18**, 169-188, doi:10.5194/bg-18-169-2021 (https://bg.copernicus.org/articles/18/169/2021/bg-18-169-2021.html) (2021).

21 Ian M. Power *et al.* Carbon Mineralization: From Natural Analogues to Engineered Systems. *Reviews in Mineralogy and Geochemistry* **77**, 305-360, doi:https://doi.org/10.2138/rmg.2013.77.9 (2013).

22 Jessica Strefler, Thorben Amann, Nico Bauer, Elmar Kriegler & Jens Hartmann. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **13**, 034010, doi:10.1088/1748-9326/aaa9c4 (https://iopscience.iop.org/article/10.1088/1748-9326/aaa9c4) (2018).

23 David W. Keith, Geoffrey Holmes, David St. Angelo & Kenton Heidel. A Process for Capturing CO2 from the Atmosphere. *Joule* **2**, 1573-1594, doi:https://doi.org/10.1016/j.joule.2018.05.006 (2018).

24 David J. Beerling *et al.* Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature* **583**, 242-248, doi:10.1038/s41586-020-2448-9 (https://www.nature.com/articles/s41586-020-2448-9) (2020).

25 Daniel S. Goll *et al.* Potential CO2 removal from enhanced weathering by ecosystem responses to powdered rock. *Nature Geoscience* **14**, 545-549, doi:10.1038/s41561-021-00798-x (2021).

26 Francesc Montserrat *et al.* Olivine Dissolution in Seawater: Implications for CO2 Sequestration through Enhanced Weathering in Coastal Environments. *Environ. Sci. Technol.* **51**, 3960-3972, doi:https://doi.org/10.1021/acs.est.6b05942 (2017).

27 Ilsa B. Kantola, Michael D. Masters, David J. Beerling, Stephen P. Long & Evan H. DeLucia. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biol. Lett.* **13**, 20160714, doi:https://doi.org/10.1098/rsbl.2016.0714 (2017).

28 Carbon Drawdown Initiative. <www.carbon-drawdown.de/home-en> (Accessed September 2021).

29 Carbon Removed. <www.carbonremoved.com> (Accessed September 2021).

30 Project Vesta. <www.projectvesta.org> (Accessed 2021).

31 OceanNETs. <www.oceannets.eu> (Accessed September 2021).

32 The Future Forest Company. <www.thefutureforestcomany.com> (Accessed September 2021).

33 The Leverhulme Centre for Climate Change Mitigation. <https://lc3m.org/> (Accessed September 2021).

34 Lennart T. Bach, Sophie J. Gill, Rosalind E. M. Rickaby, Sarah Gore & Phil Renforth. CO2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. *Frontiers in Climate* **1**, doi:10.3389/fclim.2019.00007 (https://www.frontiersin.org/articles/10.3389/fclim.2019.00007/full) (2019).

35 Igor Daniel Alves Ribeiro *et al.* Use of Mineral Weathering Bacteria to Enhance Nutrient Availability in Crops: A Review. *Front. Plant Sci.* **11**, doi:https://www.frontiersin.org/articles/10.3389/fpls.2020.590774/full (2020).

36 Elspeth Spence, Emily Cox & Nick Pidgeon. Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. *Clim. Change* **165**, 23, doi:https://doi.org/10.1007/s10584-021-03050-y (2021).

37 Romany M. Webb. The Law of Enhanced Weathering for Carbon Dioxide Removal. (Sabin Center for Climate Change Law, Columbia Law School, 2020; https://climate.law.columbia.edu/sites/default/files/content/Webb%20-%20The%20Law%20of%20Enhanced%20Weathering%20for%20CO2%20Removal%20-%20Sept.%202020.pdf).

CHAPTER 5:

MINING WASTES

Mining wastes are an important potential feedstock for carbon mineralization. Carbonation of mining wastes could remove hundreds of megatons of CO_2 from the atmosphere each year in the decades ahead, as the mining industry grows. Reaching that potential would require investments in resource assessment and mapping; protocols for measurement, monitoring and verification; industry-government-university collaborations on research and development (R&D); and favorable policies. This chapter provides background on the global mining industry and examines the potential for mining wastes to play a role in climate mitigation.

Mining sector background

An estimated 99 Gt of rock were mined for metals and minerals in 2016 (Table 1). Of this, 8.9 Gt of finely pulverized mineral wastes ("tailings") were disposed of onsite in waste storage facilities.[1] This amounts to 38 million Olympic swimming pools-worth of tailings produced in 2016 alone. Of these mine tailings, on the order of 420 Mt in a given year (~5% of total global production) are from ultramafic ore deposits and are likely to be suitable for carbon mineralization.[2]

Table 1. Estimated annual production of mine tailings with examples of the scale of stockpiled tailings.[1-4]

All rock mined annually	99 Gt/yr
Waste rock *Ore* *Tailings (less reactive to CO_2)* ***Tailings (potentially highly reactive to CO_2)***	80 Gt/yr 10.2 Gt/yr 8.48 Gt/yr 0.42 Gt/yr
Known stockpiles of chrysotile tailings	>2 Gt in North America alone
Expected tailings produced from one large nickel mine over a 30-year lifetime	0.3–1.2 Gt

At the scale of current production, the maximum carbonation potential of these 420 Mt of tailings is ~175 $MtCO_2$ per year, assuming all magnesium (Mg) and calcium (Ca) in the tailings are fully carbonated. Global annual production of ultramafic tailings is projected to at least double by 2100 owing to increasing demand for raw materials to fuel economic growth and the energy transition. Due to a projected increase in demand for metals, ultramafic mine tailings could contribute to removal of up to ~300 $MtCO_2$ from the atmosphere each year by the end of this century.[5]

Carbon mineralization in mining is attractive because it is one of the few industries that extracts and moves materials on the Gt/year-scale. Most tailings are finely pulverized, making them attractive for carbon mineralization since little or no additional energy is required for grinding. Ultramafic mine tailings produce neutral to alkaline mine waters, which are very effective at dissolving CO_2 from air.

Furthermore, decarbonizing the mining sector may require negative emissions technologies due to the role of fossil energy in fueling heavy-duty vehicles, such as mine trucks, and in generating electric power at remote locations without significant, year-round renewable resources. Carbon mineralization can play an important role in helping mining companies reach net-zero emissions.

Heavily carbonated nickel mine tailings from the Mount Keith mine, Western Australia.[4]

CO_2 removal with mine tailings

Most ultramafic tailings are produced by nickel, cobalt and platinum group element mining, with lesser amounts coming from production of chromium, diamonds and talc. Historically, chrysotile asbestos ("white asbestos") production contributed ~20–80 Mt of ultramafic tailings per year.[6] Although asbestos mining has stopped in most jurisdictions, some governments are now left with the liability of stockpiled chrysotile mine tailings. For instance, an estimated 5–8 Mt and more than 2 Gt of chrysotile asbestos mine waste remains unremediated in the United States and Canada, respectively (reviewed by Power et al., 2013).[2] Furthermore, a large modern nickel mine can produce on the order of 10–40 Mt of tailings per year over an operational lifetime of several decades.[3,4] Therefore, many more Gt of reactive material have certainly been produced within the past few centuries, although the exact scale of this stockpiled resource and its reactivity to CO_2 remain uncertain.

Many published estimates of the CO_2 sequestration potential of alkaline wastes, including mine tailings, assume that essentially every atom of magnesium and calcium can be used to bind CO_2, turning it into a solid carbonate mineral. However, the efficiency of tailings carbonation is strongly dependent on rates of mineral dissolution and CO_2 supply. Every sample of mine tailings is a mixture of several distinct magnesium- and calcium-bearing materials, each with its own dissolution rate and reactivity to CO_2, and this holds true for all alkaline wastes. Ultramafic mine tailings can have four distinct styles of reactivity with CO_2, some of which bind CO_2 very quickly and with little engineering and others that are slower and require a more engineered approach to accelerate reaction.

CO_2 can be mineralized in ultramafic mine tailings by four different processes:

1. Fast carbonation of the magnesium hydroxide mineral, brucite, which typically occurs at an average abundance of less than 5% by weight in serpentinite mine tailings.
2. Fast absorption of CO_2 by hydrotalcite minerals, which are found at up to ~10% abundance by weight in some, but not all, nickel mine tailings.
3. Fast cation exchange reactions of swelling clays, which can be used to bind CO_2 but must be driven by addition of salt treatments to tailings.[7]
4. Relatively slow dissolution of calcium and magnesium silicate minerals (olivine, serpentines and pyroxenes), which can be accelerated by adding strong acids (e.g., hydrochloric, sulfuric) during processing or tailings management.

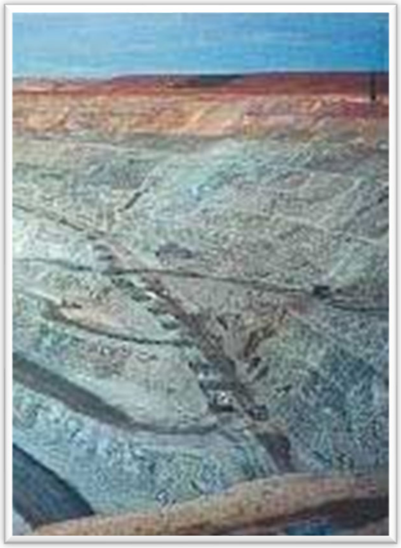
Both brucite and hydrotalcites have been shown to remove CO_2 from air in mine tailings storage facilities without any intervention. In one reported case at the Mount Keith nickel mine in Australia, these minerals are removing between 39,800 tCO_2 and 79,800 tCO_2 per year from air, offsetting 11–22% of the mine's annual greenhouse gas (GHG) emissions.[4,8] This annual rate is on the order of the amount of CO_2 sequestered by the Carbfix project between 2014 and 2021.[9] The measured sequestration rate at Mount Keith could be doubled simply by depositing the tailings in thinner flows to allow the remaining, unreacted brucite to bind CO_2 from the atmosphere.

Owing to the differential in reactivity among minerals in ultramafic mine tailings and to the extraordinarily fast reaction of brucite with CO_2, it has become conventional to think about the *percentage of emissions offsets* that can be achieved by a single mine or mining company using brucite carbonation alone. Every ore deposit or mine has its own "grade" of brucite that would make mining CO_2 neutral. For instance, the cut-off brucite grade for opening a carbon-neutral mine could be calculated using the tCO_2e emissions per year for mine operations and the mass of tailings produced annually (Box 5.1). Nevertheless, in typical ultramafic tailings, >90% of the total carbon mineralization potential comes from silicate minerals, and deposits do not always contain brucite. Thus, the slow reactivity of abundant magnesium and calcium silicate minerals in ultramafic mine tailings must be accelerated to turn mining into a negative emissions industry.

Location of resource and reserves

The amount of ultramafic rock at and near Earth's surface is vast. The mining concepts of "resource" and "reserve" provide a measure of what rocks are well understood in terms of their quality, quantity and economic viability of extraction (resource) and what rocks are known to hold a resource and could feasibly be mined using existing technology (reserve). The amount of the resource is generally much greater than that of the better-characterized reserve.

All ultramafic rocks contain nickel, but they do not always contain other desirable metal resources. The scale of ultramafic rock that could potentially be mined economically in part for carbon mineralization can therefore be estimated from Earth's known nickel resources and reserves.



The world's largest producers of nickel include Indonesia, the Philippines, Russia, New Caledonia, Australia, Canada, China and Brazil (Figure 5-1). Globally, 2.5 Mt of nickel were produced from serpentinites and nickel laterites (highly weathered serpentinites) in 2020,[10] up from about 1 Mt in 1990. Known reserves amount to 94 Mt of nickel with an estimated global resource of 300 Mt of nickel in land-based deposits averaging ≳0.5% nickel by weight. This means that the known and accessible amount of serpentinites and laterites with a nickel grade of ≳0.5% by weight is likely on the order of 60 Gt of rock. However, lower-grade nickel resources are becoming economical to mine.

Box 5-1

CALCULATING THE BRUCITE GRADE REQUIRED FOR CARBON NEUTRALITY

$Grade_{brucite}$, the *average* wt% abundance of brucite required to completely offset the CO_2 emissions from an operating mine, can be calculated using Eq. 1:

$$Grade_{brucite} = \frac{m_{CO2}}{m_{tailings}} \cdot \frac{M_{brucite}}{M_{CO2}} \cdot 100\text{ wt\%} \quad (\text{Eq. } 1)$$

Where m_{CO2} and $m_{tailings}$ are the masses of annual CO_2 emissions and annual tailings production from a mine, respectively. $M_{brucite}$ and M_{CO2} are the molar masses of brucite and CO_2. This equation assumes that a magnesium carbonate mineral, such as nesquehonite, that contains a 1:1 molar ratio of magnesium to CO_2 is produced by brucite carbonation. Eq. 1 can be rewritten for other product minerals, such as hydromagnesite, that contain a lower proportion of CO_2 relative to magnesium.

This equation can be simplified as Eq. 2 for routine use by inputting the constant values of the molar masses:

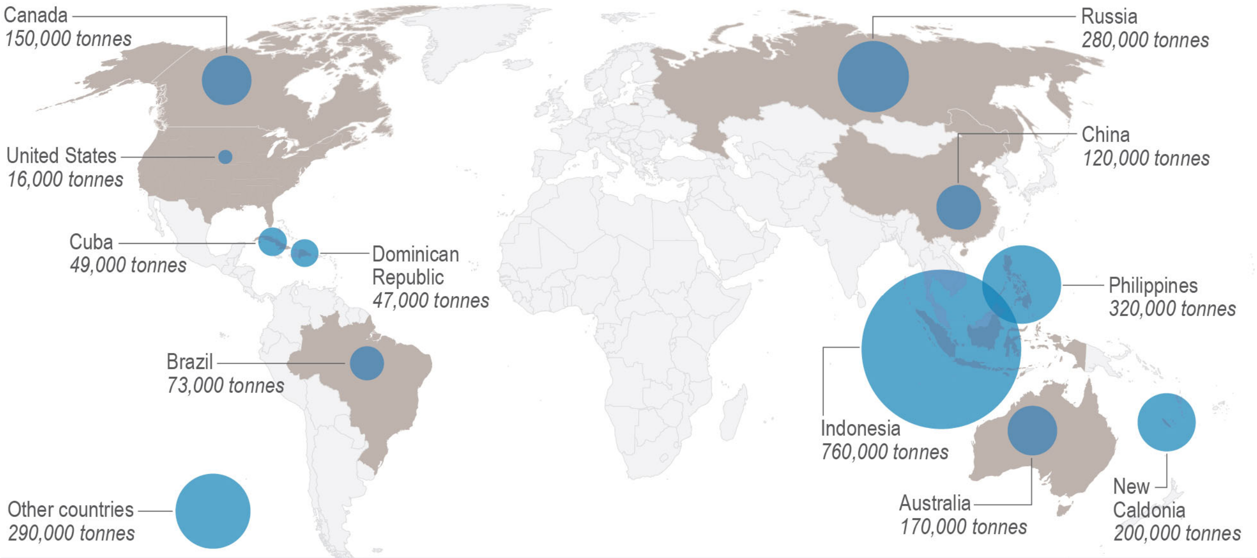
$$Grade_{brucite} = \frac{m_{CO2}}{m_{tailings}} \cdot 1.325 \cdot 100\text{ wt\%} \quad (\text{Eq. } 2)$$

Example: Using published values from the Mount Keith nickel mine in Australia[4,11] yields an average carbon neutral brucite grade of 4.5 wt% (Eq. 3).

$$Grade_{brucite} = \frac{370{,}000\text{ t}}{11{,}000{,}000\text{ t}} \cdot 1.325 \cdot 100\text{ wt\%} = 4.5\text{ wt\%} \quad (\text{Eq. } 3)$$

For instance, the giant Decar and Dumont nickel projects in Canada are under development to mine nickel at grades between 0.1 and 0.3 wt%.[12,13] The Dumont Project in Québec will produce more than 2 Mt of nickel and an estimated 1.18 Gt of ultramafic mine tailings.[13,14] Consequently, assuming nickel demand continues to grow, future estimates of resources and reserves for nickel and ultramafic rock must take into account such low-grade, high-tonnage deposits.

Although platinum group element deposits commonly contain some olivine- and serpentine-rich ultramafic rock, the bulk of the ore mined from these settings is relatively unreactive pyroxenites and mafic gabbros.[15] As such, targeted processing of serpentinite units for carbon mineralization would need to be considered at platinum group element mines using the sort of carbonation potential maps that are being developed by Vanderzee et al. (2019).[16] Locally, other ultramafic-hosted resources may be more abundant than nickel and platinum group elements. For instance,



Tonnes of nickel produced annually Values are from 2021 files from the USGS *https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-nickel.pdf*

Figure 5.1. Major world producers of nickel with their percentage production.

Botswana and South Africa could implement carbon mineralization in their world-class diamond mines.

There is potential to build capacity for carbon mineralization across the mining sector, which operates in dozens of countries around the world. Surveys are needed to assess carbonation grades, reactivity styles, and the resource and reserve of minerals that bind CO_2. Evaluations of the resource and reserve of critical metals found in ultramafic rock are also needed. Mapping of these resources should include tailings from former mine sites, ore and tailings from operating mines, and prospective ore from greenfield mineral exploration. Tailings from nickel, cobalt, chromium, diamond and chrysotile asbestos mines should be prioritized as these are likely to be the most reactive. Tailings produced by platinum group element mines would be the next priority. However, understanding the deportment and mineralogy of ultramafic rocks within these ore deposits may be more useful for future mine planning (after Vanderzee et al., 2019[16]). Countries with rich deposits of these metals and minerals and strong industry expertise, including but not limited to Australia, Botswana, Brazil, Canada, China, Russia, South Africa and the United States, could take the lead in mapping their resources and reserves for carbon mineralization in both tailings and ore deposits (e.g., Figure 5-2[17,18]). Much of this work is likely to fall under the auspices of national and regional geological surveys and could be done in partnership with the mining and university sectors to build capacity.

Current status of carbon mineralization in the mining industry

Increasingly, major mining companies are making the commitment to reach net-zero operational GHG emissions (Scopes 1 and 2) within the coming decades. For instance, Anglo American[19] has committed to achieving carbon-neutral mining by 2040, and both BHP[20] and Rio Tinto[21] have

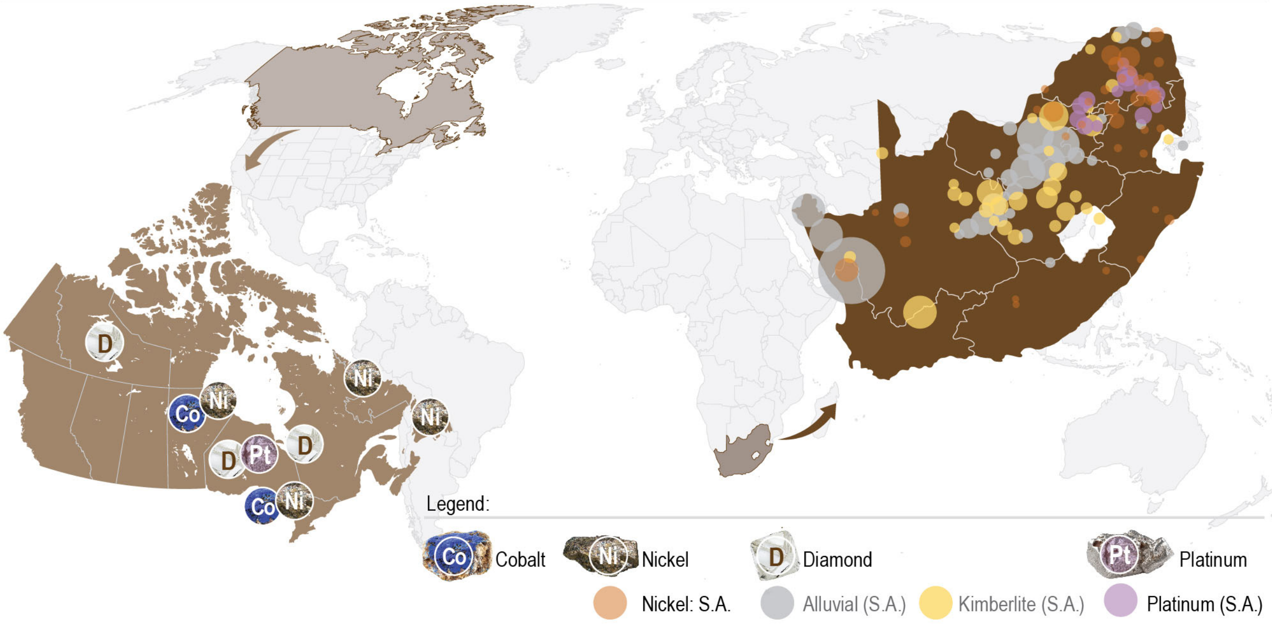


Figure 5-2. Example country maps for South Africa and Canada highlighting geographic locations of nickel, cobalt, diamond and platinum group element resources hosted by ultramafic rock suitable for carbon mineralization (reproduced from The Mining Association of Canada, 2020[17]*; South African Council for Geoscience, 2002*[18]*).*

committed to reaching net-zero emissions by 2050. De Beers,[22] the world's largest diamond miner, has committed to reaching net-zero operations nine years from now, in 2030. Carbon mineralization is one pathway that is being considered by major and junior mining companies to reach their climate ambitions.

Carbon mineralization in the mining industry is currently at the stage of small field demonstrations on the 1-m^3 to 200-m^3 scale. The earliest reports of field results have come from the following mines and projects:

1. The closed Thetford mines (Québec, Canada) where field trials were done to monitor passive, unaccelerated CO_2 removal from air into chrysotile-bearing serpentinite tailings.[23]
2. The pre-mining Dumont project (Québec, Canada) where pilots were carried out to monitor passive, unaccelerated CO_2 removal from the atmosphere into nickel-bearing serpentinite tailings.[13,24]
3. The closed Woodsreef mine (New South Wales, Australia) where field trials for accelerated tailings dissolution and microbial carbonation were done in nickel- and chrysotile-bearing serpentinite tailings.[25,26]
4. Since the mid- to late 2010s, field experiments for accelerated carbon mineralization in mine tailings have scaled up in Canada and South Africa as part of De Beers' Project CarbonVault.[27,28]

Perhaps the most important outcome of past experiments is the observation that more field trials are needed to refine monitoring techniques, optimize acceleration strategies and account for variability in tailings composition, local environmental conditions and mining practices. Other key findings from these first field trials confirm that mineral dissolution rates and slow transport of CO_2 into deeper parts of mine tailings are the key constraints on carbon mineralization rates. These trials show that accelerated carbon mineralization requires interventions such as (1) using acids to enhance the dissolution rates of silicate minerals and (2) using calcifying microorganisms or gas streams containing higher concentrations of CO_2 to supply more CO_2 into tailings.

At present, field-based acceleration of carbon mineralization stands at a technology readiness level (TRL) of 6 or 7, depending on the acceleration pathway. Physical, chemical and biological approaches to enhancing the reactivity of ultramafic mine tailings to CO_2 have been tested under operationally relevant conditions in laboratories and the field. These pathways include injection of concentrated CO_2 into tailings, the use of bioreactors employing benign microorganisms to accelerate tailings dissolution and carbonation, and a hybrid approach to tailings carbonation that leverages enhanced rock weathering in soils.

Critical metal recovery and supply security

Carbon neutrality cannot be achieved without increasing mining globally because metals are essential components of the clean energy technologies that must be deployed at vastly increased scale for the world to achieve carbon neutrality.[29] These metals include nickel, platinum, palladium and others that are typically mined from ultramafic rocks.

Carbon mineralization can be used for more efficient production of critical metals for clean energy technologies. Several recent studies have shown that employing carbon mineralization as an ore-processing technology improves recovery of nickel. For instance, Khan et al. (2021)[30] describe a model system that employs high-pressure and -temperature carbonation prior to nickel sulfide concentration using froth flotation. Their laboratory experiments show that both the rate and efficiency of nickel recovery improve for carbonated ore compared to uncarbonated ore. Wang et al. (2021)[31] have developed a method that simultaneously carbonates nickel ore while converting nickel-bearing silicates—which were previously impossible to process for nickel—into nickel sulfides that can be recovered easily using existing technology. Hamilton et al. (2020, 2021)[25,32] have demonstrated an acid heap-leaching technique that concentrates nickel, cobalt and other critical metals for recovery using conventional technologies while producing a separate, high-magnesium leachate that is ideal for carbonation. The anticipated doubling in the scale of mining from ultramafic ore deposits by the year 2100[5] offers an opportunity to expand the scale of carbon mineralization while also reframing it as a more effective and efficient approach to ore processing.

Scaling up

For carbonation of mine tailings to play a meaningful role in climate change mitigation, several steps will be required.

First, industry-government-university collaborations on R&D will be needed to foster technology transfer since much of the science behind mine tailings carbonation currently comes out of university laboratories.

Second, tools for accurate measurement and monitoring of carbon mineralization in mine tailings will need to be refined, tested at scale and deployed. Procedures for measuring and monitoring

CO_2 uptake into mine tailings are now almost ready for use in commercial laboratories. Ideally, carbon mineralization potential of mine tailings will soon be measured just as routinely as their acid-generating or acid-neutralization potential are measured today. Resources should be invested in training the skilled analytical workforce needed to manage this measurement and monitoring.

The Mount Keith nickel mine in Western Australia. (photo courtesy of BHP)

Third, a recognized international standard for verifying CO_2 sequestration in mine tailings will be needed. Some carbon registries have developed preliminary protocols for verifying CO_2 removal through mineralization. These protocols will need to be refined for use in the mining industry and gain widespread acceptance. Development work is also needed to certify international standards that can be used by commercial labs for quality assurance and quality control. Bodies such as the International Standards Organization and the US National Institute of Standards and Technology could provide standard methods and standard reference materials for this purpose.

Fourth, common tools for technoeconomic analysis (TEA) and life-cycle assessment (LCA) will be needed. These tools would support decision making at pre-commercial stages and de-risk investment by mining companies that wish to implement carbon mineralization at their operations.

Finally, supportive policies will be required. Governments should examine their regulatory frameworks for mining operations, seeking ways to provide incentives for carbon mineralization, as well as streamlining permitting processes while protecting public health and safety.

REFERENCES

1 Elaine Baker, Michael Davies, Andy Fourie, Gavin Mudd & Kristina Thygesen. “Mine tailings facilities: overview and industry trends.” in *Towards Zero Harm – A Compendium of Papers Prepared for the Global Tailings Review.* (August 2020 (https://globaltailingsreview.org/ch-ii-mine-tailings-facilities_overview-and-industry-trends/)).

2 Ian M. Power *et al.* Carbon Mineralization: From Natural Analogues to Engineered Systems. *Reviews in Mineralogy and Geochemistry* **77**, 305-360, doi:https://doi.org/10.2138/rmg.2013.77.9 (2013).

3 Ian M. Power, Gregory M. Dipple, Peter M. D. Bradshaw & Anna L. Harrison. Prospects for CO2 mineralization and enhanced weathering of ultramafic mine tailings from the Baptiste nickel deposit in British Columbia, Canada. *Int. J. Greenh. Gas Control* **94**, 102895, doi:https://doi.org/10.1016/j.ijggc.2019.102895 (2020).

4 Siobhan A. Wilson *et al.* Offsetting of CO2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining. *Int. J. Greenh. Gas Control* **25**, 121-140, doi:https://doi.org/10.1016/j.ijggc.2014.04.002 (2014).

5 Phil Renforth. The negative emission potential of alkaline materials. *Nat. Commun.* **10**, 1401, doi:10.1038/s41467-019-09475-5 (2019).

6 Erin R. Bobicki, Qingxia Liu, Zhenghe Xu & Hongbo Zeng. Carbon capture and storage using alkaline industrial wastes. *Progress in Energy and Combustion Science* **38**, 302-320, doi:https://doi.org/10.1016/j.pecs.2011.11.002 (2012).

7 Zeyen et al. (2020).

8 Stuart J. Mills *et al.* The crystal structure of stichtite, re-examination of barbertonite, and the nature of polytypism in MgCr hydrotalcites. *American Mineralogist* **96**, 179-187, doi:doi:10.2138/am.2011.3531 (2011).

9 CarbFix. <https://www.carbfix.com> (Accessed September 2021).

10 USGS: National Minerals Information Center. *Nickel Statistics and Information*, <https://www.usgs.gov/centers/nmic/nickel-statistics-and-information> (Accessed September 2021).

11 B.A. Grguric. Minerals of the MKD5 nickel deposit, Mount Keith, Western Australia. *Australian Journal of Mineralogy* **9**, 55-71 (2003).

12 Ron Britten. Regional Metallogeny and Genesis of a New Deposit Type—Disseminated Awaruite (Ni3Fe) Mineralization Hosted in the Cache Creek Terrane☼. *Economic Geology* **112**, 517-550, doi:10.2113/econgeo.112.3.517 (2017).

13 A. Gras *et al.* Isotopic evidence of passive mineral carbonation in mine wastes from the Dumont Nickel Project (Abitibi, Quebec). *Int. J. Greenh. Gas Control* **60**, 10-23, doi:https://doi.org/10.1016/j.ijggc.2017.03.002 (2017).

14 L.P. Staples, Bowen, J.M., Bernier, S.B., Warren, D.A., Scott, C.C., Duncan, J.F., Murphy, B.A., Bertrand, V.J., Scott, K.C., Latulippe, S. . Technical report on the Dumont Ni project. Launay and Trécesson Townships, Québec, Canada. (2013 (https://www.miningdataonline.com/reports/Dumont_Feasibility_07252013.pdf)).

15 N. A. Meyer *et al.* Mineral carbonation of PGM mine tailings for CO2 storage in South Africa: A case study. *Minerals Engineering* **59**, 45-51, doi:https://doi.org/10.1016/j.mineng.2013.10.014 (2014).

16 S.S.S. Vanderzee, G.M. Dipple & P.M.D. Bradshaw. Targeting Highly Reactive Labile Magnesium in Ultramafic Tailings for Greenhouse-Gas Offsets and Potential Tailings Stabilization at the Baptiste Deposit, Central British Columbia (NTS 093K/13, 14). *In Geoscience BC Summary of Activities 2018: Minerals and Mining, Geoscience BC, Report*, 109–118 (2019 (http://cdn.geosciencebc.com/pdf/SummaryofActivities2018/MM/Schol_SoA2018_MM_Vanderzee.pdf)).

17 Mining Association of Canada. *Facts and Figures 2020*, <https://mining.ca/documents/facts-figures-2020/> (2020).

18 South African Council for Geosciences. *Mineral Locality Maps of South Africa*, <https://www.geoscience.org.za/index.php/publication/downloadable-material > (2002).

19 AngloAmerican. *Climate Change & Mining*, <https://www.angloamerican.com/sustainability/environment/climate-change> (Accessed September 2021).

20 BHP Billiton. *Climate Change*, <https://www.bhp.com/sustainability/climate-change> (Accessed September 2021).

21 Rio Tinto. *Climate Change*, <https://www.riotinto.com/en/sustainability/climate-change> (Accessed September 2021).

22 De Beers Group. *Protecting the Natural World: Our 2030 Goals Explained*, <https://www.debeersgroup.com/sustainability-and-ethics/building-forever-2030-goals/protecting-the-natural-world-goals> (Accessed September 2021).

23 Karl Lechat, Jean-Michel Lemieux, John Molson, Georges Beaudoin & Réjean Hébert. Field evidence of CO2 sequestration by mineral carbonation in ultramafic milling wastes, Thetford Mines, Canada. *Int. J. Greenh. Gas Control* **47**, 110-121, doi:https://doi.org/10.1016/j.ijggc.2016.01.036 (2016).

24 A. Gras, G. Beaudoin, J. Molson & B. Plante. Atmospheric carbon sequestration in ultramafic mining residues and impacts on leachate water chemistry at the Dumont Nickel Project, Quebec, Canada. *Chem. Geol.* **546**, 119661, doi:https://doi.org/10.1016/j.chemgeo.2020.119661 (2020).

25 J. L. Hamilton *et al.* Carbon accounting of mined landscapes, and deployment of a geochemical treatment system for enhanced weathering at Woodsreef Chrysotile Mine, NSW, Australia. *Journal of Geochemical Exploration* **220**, 106655, doi:https://doi.org/10.1016/j.gexplo.2020.106655 (2021).

26 Jenine McCutcheon, Connor C. Turvey, Siobhan A. Wilson, Jessica L. Hamilton & Gordon Southam. Experimental Deployment of Microbial Mineral Carbonation at an Asbestos Mine: Potential Applications to Carbon Storage and Tailings Stabilization. *Minerals* **7**, 191 (2017).

27 Evelyn M. Mervine *et al.* Potential for offsetting diamond mine carbon emissions through mineral carbonation of processed kimberlite: an assessment of De Beers mine sites in South Africa and Canada. *Mineralogy and Petrology* **112**, 755-765, doi:10.1007/s00710-018-0589-4 (2018).

28 Robert F. Service. The Carbon Vault: Industrial waste can turn planet-warming carbon dioxide into stone. *Science*, doi:10.1126/science.abe6031 (https://www.science.org/content/article/industrial-waste-can-turn-planet-warming-carbon-dioxide-stone) (2020).

29 Olivier Vidal, Fatma Rostom, Cyril François & Gael Giraud. Global Trends in Metal Consumption and Supply: The Raw Material–Energy Nexus. *Elements* **13**, 319-324, doi:10.2138/gselements.13.5.319 (2017).

CHAPTER 6:

INDUSTRIAL WASTES

Overview

Several industrial processes generate large volumes of waste suitable for carbon mineralization. Process changes and innovation in the management of these wastes could help permanently store large amounts of CO_2, reduce local environmental hazards and cut disposal costs—a "triple win."

Industries with significant potential for carbon mineralization include iron and steel production, coal power generation, solid waste combustion and phosphoric acid production, which collectively generate billions of tons of waste per year globally. These and other industries have large legacy stockpiles of waste, collectively totaling billions more tons globally. These industrial wastes contain significant amounts of calcium (Ca), magnesium (Mg) and other minerals that can react with CO_2 to form stable mineral carbonates. The wastes are often located near point sources of CO_2 emissions.

Industrial wastes have the potential to remove hundreds of millions of tons of CO_2 globally each year through carbon mineralization, with significant ancillary benefits. This chapter examines the potential use of industrial wastes as feedstocks for carbon mineralization.

Iron and steel slag

The iron and steel industry generates a large amount of calcium- and magnesium-rich solid waste, generically known as slag. This material comes from the ore and from decomposition of carbonate minerals (such as limestone) that are added to furnaces during iron and steel production for the purpose of removing impurities, particularly silicon and aluminum. Although precise data are not available, the global production of slag in 2019 was approximately 320–384 million tons from iron production and 190–280 million tons from steel production.[1] Globally, this slag has the potential to mineralize up to 268 $MtCO_2$ per year, based on current iron and steel production. Legacy slag (that is, slag previously produced and stored as waste) could provide an additional cumulative total of 8.2 $GtCO_2$ of carbon mineralization.[2]

Slag can be mineralized in three ways.

- The first method is direct gas-solid mineralization, in which gaseous CO_2 is reacted directly with solid slag. This method is limited by slow reaction rates, due in part to passivation: as the outer surface of bulk slag reacts with CO_2, it can form solid carbonate layers that are impermeable to CO_2, preventing further reaction with slag material deeper within the bulk.
- The second method is direct aqueous mineralization, in which CO_2 is first dissolved in pressurized water, which is then exposed to slag. This method tends to be faster than direct gas-solid mineralization, but the dissolution rate of calcium and magnesium can limit the overall reaction. More research is needed on understanding the optimal combination of pressure, temperature, slag grain size and other factors to increase the speed of this process.

- The third method is indirect mineralization, in which calcium and magnesium are first extracted from slag by acid leaching, followed by dissolution of pressurized CO_2 in the leachate and precipitation of carbonate. This approach is more complex, but it allows the conditions of leaching, CO_2 dissolution and carbon mineralization to be separately optimized.[2,3]

Figure 6-1. Iron slag being poured from slag pot.

The actual extent of carbon mineralization achieved by these methods varies significantly with different slag sources and processing steps; values ranging from 0.1–0.4 tCO_2 per ton of slag have recently been reported, with reaction timescales of several hours.[4,5] While the overall storage capacity is large (CaO + MgO concentrations can reach tens of wt%), much slag resembles feldspar-rich mafic rocks in which the abundance of slowly reacting alumino-silicate and pyroxene minerals can lead to slow CO_2 uptake. Processing steps can partly overcome this slow reaction rate but negatively impact the overall carbon storage potential on a life-cycle basis.

Because these methods are all currently envisaged as using purified, pressurized CO_2, they are all designed for CO_2 storage, rather than removal from air. However, hybrid methods for combined capture and storage—for example, using flue gas—could be considered.

Despite its large potential, the use of slag for mineralization faces several important challenges. The first challenge is that a large fraction of slag produced in OECD countries is already utilized for other purposes. In particular, during iron-making in blast furnaces (BF), approximately 0.25–0.50 tons of slag are generated per ton of pig iron produced. When this BF slag is rapidly water-cooled (quenched), it forms a glassy, granulated material (known as ground granulated BF slag or GGBS) that can be crushed or milled and used as a supplementary cementitious material (SCM) to partly replace clinker produced by cement manufacture. This utilization of slag avoids emissions from clinker production, corresponding to approximately 0.58 tCO_2 per ton of slag, which is higher than the emissions removal potential of slag mineralization, which is 0.24–0.52 tCO_2 per ton of slag. Therefore, in general this slag should not be redirected from its current use.[1,6,7]

By contrast, slag produced in basic oxygen furnaces (BOF) or electric arc furnaces (EAF) during steel-making is not as appropriate for displacing cement. This slag is also of limited use for related applications, such as replacing aggregate in concrete, because it contains large amounts of free lime (CaO), leading to swelling upon reaction with air to form $Ca(OH)_2$ and $CaCO_3$ and subsequent damage in civil engineering applications. (Accelerated hydration through steam treatment can mitigate this issue in some cases.[8]) Because of its relatively low silicon content and high iron content, steel slag rarely vitrifies and instead forms a crystalline, gravel-sized material that is quite hard due to the presence of high amounts of iron oxide (Fe_2O_3).[9]

Steel slag is of interest for mineralization because of its high calcium content, which is commonly over 33 wt%.[10] Similar to BF slag, over 85% of steel slag in Japan, Europe and the United States is used for purposes such as blast furnace re-use and agriculture.[11] However, the life-cycle CO_2 emissions impacts of these uses are not as well understood as those of GGBS and may not be as beneficial from a CO_2 perspective as mineralization.

In contrast to OECD economies, utilization rates of slag in China and India—the world's first and second largest steel producers—are much lower, at approximately 30%.[12] In China, US- and China-based Greenore is developing technology to treat steel slag with CO_2, producing carbonates and other products. In India, steel slag disposal is likely to become an ever more acute problem as the country seeks to triple its steel production by 2030.[13] While carbon mineralization is one option, numerous other uses with higher inherent economic value are also under active consideration.[14] Absent an effective carbon price or focused government policy, carbon mineralization alone appears unlikely to emerge as a primary utilization pathway. An important area for new research is therefore to develop processes that mineralize steel slag and produce valorized products.[15]

The second major challenge in using slag for mineralization is the fact that it is highly heterogenous, with slag from different iron and steel facilities having extremely different characteristics. Slag's chemical content varies due to different ores and different amounts of recycled steel content, as well as different carbonate additives. Slag's mineral content and particle size vary due to different cooling and heat recovery techniques. Both forms of heterogeneity can have large impacts on carbonation reaction rates and on the total fraction of slag that reacts with CO_2. In general, when direct gas-solid mineralization processes are used, fully crystalline slags undergo much more complete mineralization than poorly crystalline and glassy slags with the same composition. Additional grinding of poorly crystalline and glassy slags can compensate for this, but the required energy input generally leads to greater overall emissions.[7]

In addition to ongoing slag production, legacy slag represents an important potential mineralization resource that faces its own set of challenges. China alone has roughly 2 billion tons of legacy steel slag waste; although this waste is not well characterized.[16] In fact, few countries have comprehensive mapping or characterization of legacy iron and steel slag. A rare exception is the United Kingdom, whose long history of industrialization has resulted in an estimated 190 million tons of legacy slag.[17] Almost all this material likely remains uncarbonated, although a substantial amount (approximately 38%) is under urban or suburban developments, making recovery challenging.[18] A smaller but still significant additional fraction is in ecologically sensitive areas, also rendering recovery problematic.

Recommendations:

- Expand research on the optimum use of slag from a system-level life-cycle standpoint, including tradeoffs with other slag uses.
- Expand applied research on the optimum methods for reacting CO_2 with slag to achieve fast reaction rates and high conversion of calcium and magnesium to carbonates.
- Expand applied research on improved methods for cooling slag to simultaneously optimize heat recovery and preparation for mineralization.

- Expand applied research on efficient chemical, mineralogical and morphological characterization of steel slag.
- Expand efforts to improve understanding of legacy steel slag waste, including the quantities, characteristics and locations of slag heaps.
- Increase policy support for use of iron and steel slag as carbon mineralization feedstock, including launching a series of industrial pilot projects.

Fly ash

Fly ash is a byproduct of burning coal and other fuels such as municipal solid waste. It takes the form of a fine dust that is mixed with the combustion flue gas and, to protect air quality, is usually removed before it reaches the smokestack by mechanical or electrostatic precipitators. Fly ash consists of a mixture of small (approximately 10-micron-diameter) glassy beads rich in silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and lime (CaO) as the main components. The exact composition of the fly ash depends strongly on the fuel that was burned and the combustion conditions. In general, lignite and sub-bituminous coal produce fly ash with lime content over 20%, while bituminous coal and anthracite produce fly ash with less than 10% lime.[19]

Figure 6-2. *Fly ash pond/landfill.*

One of the major advantages of using fly ash for carbon mineralization is that little to no pretreatment, such as grinding, is required since the fly ash is already fine-grained with high surface area. However, the amount of carbon uptake by weight is limited because of its relatively low content of CaO + MgO compared to other industrial wastes. Fly ash with high lime content is the most desirable for mineralization and has been demonstrated to react with CO_2 to form cemented solids that can be used in concrete, with a CO_2 uptake of 9 wt%.[20] Ongoing research focuses on process improvements for increasing the rate and extent of CO_2 uptake.[21-25] Low-lime fly ash shows lower potential for mineralization but continues to receive some research attention.[26] In general, the optimum reaction conditions for efficient carbonation, including reaction temperature and pressure, CO_2 partial pressure, and solid-to-liquid ratio, remain the subject of active research.[19] So far, most studies have used purified CO_2 as a reactant, thus investigating the potential for storage, but not removal from air. However, the fine-grained nature and high lime content of fly ash suggest that this material could also be used for CO_2 removal from ambient air. However, some fraction of the lime content may be embedded in glassy spheres and therefore unreactive, reducing the overall mineralization potential. In this case, some additional pretreatment may be advantageous.

Fly ash is the primary solid waste stream from coal-fired power plants, with 250–300 kg produced during the combustion of one ton of coal.[19,27,28] As a result, approximately 1 billion tons are produced worldwide each year.[29] Globally, a large fraction of this waste is dumped in ash ponds or landfills for disposal, despite the potential environmental hazards from leaching of heavy metals. In some countries, significant amounts of fly ash are instead utilized for beneficial purposes, including as an SCM, partly replacing cement, although it cannot be added to cement in as high a proportion as blast furnace slag.[30] Fly ash is also used in agriculture as a soil amendment, in mine reclamation as backfill material, and in the production of construction materials, such as bricks and ceramics. Rates of re-use are extremely high in Japan and Europe (over 90%), with lower rates in the United States, China and India (ranging from 50–80%).

Because of high re-use rates and declining coal-fired power generation in many OECD countries, the largest opportunities for fly ash mineralization are in China and India. China alone produced 540 million tons of coal fly ash in 2019.[28] One challenge for increasing coal fly ash utilization in China is a regional imbalance in supply and demand. Coal-fired generation in the west and north of the country is far from fly ash demand in the urbanized southeastern coast, and the low value-to-weight ratio makes fly ash uneconomical to transport long distances. Declining rates of construction may also soon lead to reduced demand for fly ash in concrete and paving, highlighting the need to identify new utilization opportunities. Mineralization has received some research attention in this context. However, many potentially high-value uses other than mineralization are being actively researched, including as a source of aluminum (displacing bauxite) and in the treatment of wastewater.[31] India's production of coal fly ash has been steadily increasing, with 226 million tons produced in 2019–2020.[32] Utilization rates have also been steadily increasing, led by construction materials (cement/bricks/ceramics), land reclamation, ash dyke raising and roads. Mineralization has received relatively little attention as an opportunity for further increasing fly ash utilization.

The issue of multiple existing and proposed uses of fly ash means that careful system analysis is needed to identify the optimal use of this material. However, in some cases there are useful synergies between mineralization and valorization of certain fly ash types for additional use. For example, fly ash from fluidized bed boilers often contains a relatively high fraction of free lime, exceeding the maximum standard for use in cement production. This free lime can be reacted with CO_2 in the presence of water, leading to mineralization and reduction of the free lime content to the point that the treated fly ash can be used for cement applications.[33] Further research on these synergistic approaches to mineralization and valorization is needed.

Legacy coal fly ash also represents a major environmental burden. It contains heavy metals, including arsenic and lead, which can contaminate soil and groundwater; wind can also blow ash particles into the air, leading to poor air quality and human exposure to these toxins when inhaled.[34] Mineralization would largely eliminate these problems by fixing heavy metals in solid carbonates. Russia is estimated to have over 1.5 billion tons of legacy coal fly ash as of 2017,[35] and China has over 3 billion tons as of 2020.[31] This material is stored in a range of forms, including in ash ponds and landfills. While these locations are generally better mapped than legacy iron and steel slag, they are rarely fully characterized and require better resource assessment as a potential mineralization feedstock.

Recommendations:

- Expand applied research on process development and intensification for mineralization of fly ash, particularly for synergistic mineralization and valorization of resulting products.
- Expand systems and life-cycle assessment (LCA) research on identifying the optimum use of fly ash, particularly in the context of existing and emerging uses other than mineralization.
- Expand efforts to improve the understanding of legacy fly ash waste, including the quantities, characteristics and locations of ash ponds and other storage sites.
- Increase policy support for the use of fly ash as carbon mineralization feedstock, including launching a series of industrial pilot projects.

Phosphogypsum

The production of phosphoric acid (primarily for fertilizer applications) from phosphorous ore produces phosphogypsum waste. Approximately 5 tons of waste are produced for each ton of phosphoric acid. Phosphogypsum primarily consists of the mineral gypsum (calcium sulfate dihydrate—$CaSO_4 \bullet 2H_2O$). While conventional gypsum is used as a construction material, phosphogypsum commonly contains trace amounts of radioactive uranium, thorium and radium and is generally not approved for industrial re-use. As a result, large amounts are stockpiled globally with significant associated environmental hazards.

Globally, approximately 200 million tons of phosphogypsum are produced annually, with a utilization rate of only 10–15%, primarily in agriculture and construction materials.[36] China alone produces roughly 75 million tons per year, with legacy stocks of approximately 600 million tons.[28] Russia has legacy stocks of approximately 500 million tons.[36] In the United States, over 1 billion tons of legacy stocks are present, concentrated in Florida.[37] Until 2020, when the use of phosphogypsum was approved for road construction,[38] its use was largely prohibited in the United States due to its radioactive content.

Because of its high calcium content, phosphogypsum has high potential for carbon mineralization. Relatively little pre-treatment (grinding) is required due to its small particle size. The most studied phosphogypsum mineralization process is based on CO_2 capture using purified CO_2 as a reactant. Treatment with chilled aqueous ammonia is followed by reaction with solid phosphogypsum to produce calcium carbonate ($CaCO_3$) and ammonium sulfate ($(NH_4)_2SO_4$).[39-41] Research has also focused on alternative pathways with enhanced product purity, including ones that react phosphogypsum with waste from aluminum anodizing.[42-45] In general, these processes achieve almost complete (>95%) carbonation of calcium ions with fast reaction rates. In many cases, the produced calcium carbonate is pure enough for industrial re-use, leading to significant revenue

Figure 6-3. Phosphogypsum stack.

streams. Notably, CO_2 storage via carbonation of phosphogypsum using purified CO_2, captured elsewhere, can reduce the environmental burden of phosphogypsum disposal, and treatment of legacy phosphogypsum could help avoid threats to groundwater from storage stacks.[46] An important aspect of the use of phosphogypsum mineralization is the fate of the ammonium sulfate that is produced from the sulfur initially bound in the gypsum reactant. This material can be used as a fertilizer but would saturate relevant markets if it were produced at large scale, limiting the suitability of phosphogypsum mineralization for CO_2 removal from air.

Key areas for further research include process intensification and improved routes to high-purity calcium carbonate. Much of the research on phosphogypsum mineralization is also relevant to byproduct gypsum from flue gas desulfurization at coal-fired power plants (whose annual production rate is about half that of phosphogypsum), and improved insights could be gained from further integrating research on these related materials.[47,48] Also, despite the promise of carbon mineralization using industrial gypsum for CO_2 storage, comprehensive LCAs and cost analyses are largely unavailable and should be the focus of significant research.

Recommendations:

- Pursue cost and LCA research on phosphogypsum mineralization.
- Expand applied research on process intensification for phosphogypsum mineralization, as well as mineralization of other industrial gypsum sources.
- Increase policy support for the use of phosphogypsum as carbon mineralization feedstock, including launching a series of industrial pilot projects.

REFERENCES

1 Kenneth C. Curry (USGS). *U.S. Geological Survey, Mineral Commodity Summaries: Iron and Steel Slag*, <https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-iron-steel-slag.pdf> (2020).

2 Corey A. Myers, Takao Nakagaki & Kosei Akutsu. Quantification of the CO2 mineralization potential of ironmaking and steelmaking slags under direct gas-solid reactions in flue gas. *Int. J. Greenh. Gas Control* **87**, 100-111, doi:https://doi.org/10.1016/j.ijggc.2019.05.021 (2019).

3 Qing Zhao *et al.* Co-treatment of Waste From Steelmaking Processes: Steel Slag-Based Carbon Capture and Storage by Mineralization. *Frontiers in Chemistry* **8**, doi:10.3389/fchem.2020.571504 (2020).

4 R. Baciocchi *et al.* Thin-film versus slurry-phase carbonation of steel slag: CO2 uptake and effects on mineralogy. *Journal of Hazardous Materials* **283**, 302-313, doi:https://doi.org/10.1016/j.jhazmat.2014.09.016 (2015).

5 P. Nielsen, M. A. Boone, L. Horckmans, R. Snellings & M. Quaghebeur. Accelerated carbonation of steel slag monoliths at low CO2 pressure – microstructure and strength development. *Journal of CO2 Utilization* **36**, 124-134, doi:https://doi.org/10.1016/j.jcou.2019.10.022 (2020).

6 Shubhi Dubey, Ashita Singh & Suresh Singh Kushwah. Utilization of iron and steel slag in building construction. *AIP Conference Proceedings* **2158**, 020032, doi:10.1063/1.5127156 (2019).

7 Corey Adam Myers & Takao Nakagaki. Effect of Solidification and Cooling Methods on the Efficacy of Slag as a Feedstock for CO2 Mineralization. *ISIJ International* **58**, 211-219, doi:10.2355/isijinternational.ISIJINT-2017-478 (2018).

8 Praveen Kumar, D Satish Kumar, K Marutiram & SMR Prasad. Pilot-scale steam aging of steel slags. *Waste Management & Research* **35**, 602-609, doi:10.1177/0734242x17694247 (2017).

9 Irem Zeynep Yildirim & Monica Prezzi. Chemical, Mineralogical, and Morphological Properties of Steel Slag. *Advances in Civil Engineering* **2011**, 463638, doi:10.1155/2011/463638 (2011).

10 Krishna R. Reddy, Archana Gopakumar & Jyoti K. Chetri. Critical review of applications of iron and steel slags for carbon sequestration and environmental remediation. *Reviews in Environmental Science and Bio/Technology* **18**, 127-152, doi:10.1007/s11157-018-09490-w (2019).

11 Raghavendra Ragipani, Sankar Bhattacharya & Akkihebbal K. Suresh. A review on steel slag valorisation via mineral carbonation. *Reaction Chemistry & Engineering* **6**, 1152-1178, doi:10.1039/D1RE00035G (2021).

12 Jianlong Guo, Yanping Bao & Min Wang. Steel slag in China: Treatment, recycling, and management. *Waste Management* **78**, 318-330, doi:https://doi.org/10.1016/j.wasman.2018.04.045 (2018).

13 India Brand Equity Foundation (IBEF). *Iron & Steel Industry in India*, <https://www.ibef.org/industry/steel.aspx> (Accessed September 2021).

14 Somnath Kumar. Recent trends in slag management & utilization in the steel industry. **1**, 94-102 (2019).

15 Shu-Yuan Pan *et al.* CO2 Mineralization and Utilization using Steel Slag for Establishing a Waste-to-Resource Supply Chain. *Scientific Reports* **7**, 17227, doi:10.1038/s41598-017-17648-9 (2017).

16 LV Jingwen 36Kr (Nikkei Asia). *Chinese startup tackles 2bn tons of slag with new technology*, <https://asia.nikkei.com/Business/36Kr-KrASIA/Chinese-startup-tackles-2bn-tons-of-slag-with-new-technology> (2020).

17 Alex L. Riley *et al.* Legacy iron and steel wastes in the UK: Extent, resource potential, and management futures. *Journal of Geochemical Exploration* **219**, 106630, doi:https://doi.org/10.1016/j.gexplo.2020.106630 (2020).

18 Huw Pullin *et al.* Atmospheric Carbon Capture Performance of Legacy Iron and Steel Waste. *Environ. Sci. Technol.* **53**, 9502-9511, doi:10.1021/acs.est.9b01265 (2019).

19 Ukwattage NL and Ranjith PG. Accelerated Carbonation of Coal Combustion Fly Ash for Atmospheric Carbon dioxide Sequestration and Soil Amendment: An Overview. *Journal of Pollution Effects & Control* **6: 210**, doi:10.4172/2375-4397.1000210 (https://www.longdom.org/open-access/accelerated-carbonation-of-coal-combustion-fly-ash-for-atmosphericcarbon-dioxide-sequestration-and-soil-amendment-an-overview-2375-4397-1000210.pdf) (2018).

20 Zhenhua Wei *et al.* Clinkering-free cementation by fly ash carbonation. *Journal of CO2 Utilization* **23**, 117-127, doi:https://doi.org/10.1016/j.jcou.2017.11.005 (2018).

21 Agnieszka Ćwik, Ignasi Casanova, Kwon Rausis, Nikolaos Koukouzas & Katarzyna Zarębska. Carbonation of high-calcium fly ashes and its potential for carbon dioxide removal in coal fired power plants. *Journal of Cleaner Production* **202**, 1026-1034, doi:https://doi.org/10.1016/j.jclepro.2018.08.234 (2018).

22 Long Ji *et al.* CO2 sequestration by direct mineralisation using fly ash from Chinese Shenfu coal. *Fuel Processing Technology* **156**, 429-437, doi:https://doi.org/10.1016/j.fuproc.2016.10.004 (2017).

23 Jung Hyun Kim & Woo Teck Kwon. Semi-Dry Carbonation Process Using Fly Ash from Solid Refused Fuel Power Plant. *Sustainability* **11**, 908 (2019).

24 Katja Ohenoja, Jouni Rissanen, Paivo Kinnunen & Mirja Illikainen. Direct carbonation of peat-wood fly ash for carbon capture and utilization in construction application. *Journal of CO2 Utilization* **40**, 101203, doi:https://doi.org/10.1016/j.jcou.2020.101203 (2020).

25 Jakub Sobala *et al.* The Mineral Carbonation Process of High Calcium Fly Ash under Elevated Carbon Dioxide Pressure and Temperature. *Scholars International Journal of Chemistry and Material Sciences* **3(6)**, 71-77, doi:10.36348/sijcms.2020.v03i06.003 (https://saudijournals.com/media/articles/SIJCMS_36_71-77_c.pdf) (2020).

26 Alicja Uliasz-Bocheńczyk & Eugeniusz Mokrzycki. The potential of FBC fly ashes to reduce CO2 emissions. *Scientific Reports* **10**, 9469, doi:10.1038/s41598-020-66297-y (2020).

27 Shengxiang Jin *et al.* Comparison and Summary of Relevant Standards for Comprehensive Utilization of Fly Ash at Home and Abroad. *IOP Conference Series: Earth and Environmental Science* **621**, 012006, doi:10.1088/1755-1315/621/1/012006 (2021).

28 Junlin Meng, Wenjie Liao & Guoquan Zhang. Emerging CO2-Mineralization Technologies for Co-Utilization of Industrial Solid Waste and Carbon Resources in China. *Minerals* **11**, 274 (2021).

29 Shanjida Sultana *et al.* "Coal Fly Ash Utilisation and Environmental Impact" in *Clean Coal Technologies: Beneficiation, Utilization, Transport Phenomena and Prospective* (eds Rajesh Kumar Jyothi & Pankaj Kumar Parhi) 381-402 (Springer International Publishing, 2021).

30 David J. M. Flower & Jay G. Sanjayan. Green house gas emissions due to concrete manufacture. *The International Journal of Life Cycle Assessment* **12**, 282, doi:10.1065/lca2007.05.327 (2007).

31 Yang Luo *et al.* Utilization of coal fly ash in China: a mini-review on challenges and future directions. *Environmental Science and Pollution Research* **28**, 18727-18740, doi:10.1007/s11356-020-08864-4 (2021).

32 Government of India: Ministry of Power. *Report On Fly Ash Generation at Coal/Lignite-Based Thermal Power Stations and its Utilization in the Country for the Year 2019 -20*, <https://cea.nic.in/wp-content/uploads/tcd/2021/01/flyash_2019-20.pdf> (2020).

33 Marian Jacek Łączny, Sebastian Iwaszenko & Adam Smoliński. Process Kinetics of the Carbonation of Fly Ashes: A Research Study. *Materials* **14**, 253 (2021).

34 Kristina M. Zierold & Chisom Odoh. A review on fly ash from coal-fired power plants: chemical composition, regulations, and health evidence. *Reviews on Environmental Health* **35**, 401-418, doi:10.1515/reveh-2019-0039 (2020).

35 Oksana Marinina, Marina Nevskaya, Izabela Jonek-Kowalska, Radosław Wolniak & Mikhail Marinin. Recycling of Coal Fly Ash as an Example of an Efficient Circular Economy: A Stakeholder Approach. *Energies* **14**, 3597 (2021).

36 Yelizaveta Chernysh, Olena Yakhnenko, Viktoriia Chubur & Hynek Roubík. Phosphogypsum Recycling: A Review of Environmental Issues, Current Trends, and Prospects. *Applied Sciences* **11**, 1575 (2021).

37 H. Liang, P. Zhang, Z. Jin & D. DePaoli. Rare earths recovery and gypsum upgrade from Florida phosphogypsum. *Minerals & Metallurgical Processing* **34(4)**, 201-206 (2017).

38 United States Environmental Protection Agency (US EPA). *EPA Approves Use of Phosphogypsum in Road Construction*, <https://www.epa.gov/newsreleases/epa-approves-use-phosphogypsum-road-construction> (2020).

39 M. Contreras *et al.* Fractionation and fluxes of metals and radionuclides during the recycling process of phosphogypsum wastes applied to mineral CO2 sequestration. *Waste Management* **45**, 412-419, doi:https://doi.org/10.1016/j.wasman.2015.06.046 (2015).

40 Hannu-Petteri Mattila & Ron Zevenhoven. Mineral Carbonation of Phosphogypsum Waste for Production of Useful Carbonate and Sulfate Salts. *Frontiers in Energy Research* **3**, doi:10.3389/fenrg.2015.00048 (2015).

41 Xolani Msila, David Gordon Billing & Werner Barnard. Capture and storage of CO2 into waste phosphogypsum: the modified Merseburg process. *Clean Technologies and Environmental Policy* **18**, 2709-2715, doi:10.1007/s10098-016-1157-4 (2016).

42 Qiuju Chen, Wenjin Ding, Hongjuan Sun, Tongjiang Peng & Guohua Ma. Indirect mineral carbonation of phosphogypsum for CO2 sequestration. *Energy* **206**, 118148, doi:https://doi.org/10.1016/j.energy.2020.118148 (2020).

43 Wenjin Ding, Qiuju Chen, Hongjuan Sun & Tongjiang Peng. Modified mineral carbonation of phosphogypsum for CO2 sequestration. *Journal of CO2 Utilization* **34**, 507-515, doi:https://doi.org/10.1016/j.jcou.2019.08.002 (2019).

44 I. Romero-Hermida *et al.* New method for carbon dioxide mineralization based on phosphogypsum and aluminium-rich industrial wastes resulting in valuable carbonated by-products. *Journal of CO2 Utilization* **18**, 15-22, doi:https://doi.org/10.1016/j.jcou.2017.01.002 (2017).

45 Wei Zhang *et al.* An efficient methodology to use hydrolysate of phosphogypsum decomposition products for CO2 mineral sequestration and calcium carbonate production. *Journal of Cleaner Production* **259**, 120826, doi:https://doi.org/10.1016/j.jclepro.2020.120826 (2020).

46 Daljit Sandhu *et al.* Fate and transport of radioactive gypsum stack water entering the Floridan aquifer due to a sinkhole collapse. *Scientific Reports* **8**, 11439, doi:10.1038/s41598-018-29541-0 (https://www.nature.com/articles/s41598-018-29541-0) (2018).

47 Nadeesha H. Koralegedara, Patricio X. Pinto, Dionysios D. Dionysiou & Souhail R. Al-Abed. Recent advances in flue gas desulfurization gypsum processes and applications – A review. *Journal of Environmental Management* **251**, 109572, doi:https://doi.org/10.1016/j.jenvman.2019.109572 (2019).

48 Bo Wang, Zihe Pan, Huaigang Cheng, Zhien Zhang & Fangqin Cheng. A review of carbon dioxide sequestration by mineral carbonation of industrial byproduct gypsum. *Journal of Cleaner Production* **302**, 126930, doi:https://doi.org/10.1016/j.jclepro.2021.126930 (2021).

CHAPTER 7:

CEMENT AND CONCRETE

The cement and concrete industry is a significant source of greenhouse gas (GHG) emissions—roughly 8% of the global total.[1] Several carbon mineralization processes could significantly reduce these emissions. This chapter provides an overview of the cement and concrete industry and discusses three processes with the potential to reduce its emissions—mixing carbonation, carbonation curing and production of synthetic aggregates.

Overview of the cement and concrete industry

In 2019, approximately 4.1 Gt of cement was produced globally, making cement one of the few products that is manufactured at the gigaton scale.[2] Despite this enormous scale, cement is never consumed directly; instead, it is mixed with water and aggregate materials (sand, gravel and stone) to produce concrete, which is then used in construction. The total amount of concrete consumed globally is therefore much larger, approximately 30 Gt in 2019.

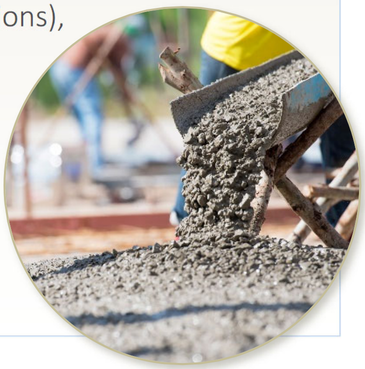
Cement and its precursor, clinker, tend to be produced in proximity to sources of limestone, which is used as feedstock.[3] Much of cement production is consolidated among a small number of large multinational producers with annual sales over $10 billion.[4] By contrast, concrete production is overwhelmingly local and carried out at much smaller scales close to areas where construction occurs because (1) the low value-to-weight ratio of finished concrete makes longer distance

Box 7.1

CEMENT AND CONCRETE

Concrete that is used to build roads, buildings and bridges is a mixture of cement (also known as binder), water and solid aggregate materials, such as gravel, sand and crushed stone (also known as filler).

Typical concrete includes 10–15% cement, 15–20% water, and 60–75% aggregate by volume. Conventional cement, called Ordinary Portland Cement (OPC), is manufactured by quarrying and crushing limestone and clay and then heating it in a rotating kiln at temperatures around 1400°C. This process drives off CO_2 and other gases (process emissions), resulting in small nodules of a material known as clinker. After cooling, clinker is ground to a fine powder and mixed with additives to produce cement. One way to lower CO_2 emissions from cement production is by substituting some clinker with supplementary cementitious materials (SCMs) rich in CaO, such as blast furnace slag and fly ash, which is common practice in regions where these materials are widely available.



transportation uneconomical and (2) concrete permanently hardens only a few hours after production. As an illustration of this industry structure, the United States has only approximately 100 cement plants, while concrete plants number in the thousands.[5] Global demand for cement and concrete is projected to grow by 12–23% by 2050 compared to 2014, with much of the growth in Asia.[6]

Emissions associated with cement and concrete production

The production of cement has estimated life-cycle emissions of 0.6–0.8 tCO_2e per ton of cement, due primarily to process emissions.[7] The life-cycle emissions of concrete are approximately 0.15–0.23 tCO_2e per ton of concrete.[8] These emissions are lower on a weight basis because cement is a small fraction of the overall weight of concrete, and the emissions associated with the other ingredients of concrete (water and aggregate) are relatively small. Many methods have been proposed, tested and (in some cases) implemented for reducing the emissions of concrete, including use of SCMs (as discussed above), electric or hydrogen-fired kilns, point-source carbon capture during cement manufacturing and carbon mineralization.[9,10] If these methods are all implemented simultaneously, finished concrete has the theoretical potential to be carbon-negative, a prospect that is tremendously important given the enormous global consumption of concrete.

The following discussion focuses on carbon mineralization methods for cement and concrete. In general, these methods are compatible with the other cement and concrete emissions–reducing strategies noted in the previous paragraph. Research on carbon mineralization for cement and concrete should therefore not be pursued in isolation or at the expense of other pathways toward low-carbon or carbon-negative concrete but rather as part of a holistic effort.

A wide array of mineralization/carbonation methods for cement and concrete have been proposed and explored. The most mature of these are mixing carbonation (injecting purified CO_2 during concrete mixing), carbonation curing (replacing water/steam with purified CO_2 during curing), and the production of synthetic aggregate. Each of these methods has advantages and disadvantages, as will be discussed below. Because the first two processes are often viewed as adding carbon to concretes, they are commonly referred to as "carbonation" rather than "carbon mineralization."

Mixing carbonation is primarily used for ready-mix concrete, which is usually delivered to construction sites by mixing (barrel) trucks. This process consists of injecting a small dose of pure (gaseous) CO_2 into the concrete mix during batching, which leads to the formation of nano-scale solid calcium carbonate ($CaCO_3$) particles distributed evenly throughout the mix, which stores carbon for the lifetime of the concrete, approximately 50–100 years.

While some early work on mixing carbonation aimed to maximize the amount of CO_2 injected into the mix, large amounts of CO_2 can have negative impacts on the performance of the concrete. However more recent work has shown that a relatively small dose of CO_2 (~0.15% of the weight of cement or ~0.02% of the weight of concrete) leads to improvements in performance, the most important of which is an increase in the compressive strength of the finished concrete.[11] Because concrete strength is primarily determined by the amount of cement in the mix (more cement leads to higher strength), this increase in strength enables a corresponding reduction in cement content to achieve the same overall performance. This results in economic savings and emissions reductions because cement is both the most expensive and the most emissions-intensive component of concrete.[12] Mixing carbonation also has favorable impacts on other concrete properties, including decreasing set time and increasing durability.

Mixing carbonation has gained significant traction in the market, with Canada-based CarbonCure offering commercial products with widespread uptake. A key commercial advantage of the technology is that it requires only minor process changes to conventional concrete production, with low-cost additional equipment, making it relatively easy to adopt by most concrete producers.

Carbonation curing is primarily applicable to precast and masonry concrete products, which are conventionally cured using steam in closed reactors shortly after casting. Carbonation curing partly or completely replaces this steam with pure CO_2 gas.[13] During conventional curing of ordinary portland cement (OPC), reactions between water and cement produce calcium-silicate-hydrate (C-S-H) crystals—whose interlocking structure provides strength—and calcium hydroxide. In carbonation curing, C-S-H is still produced but, instead of calcium hydroxide, the reaction leads to particles of solid calcium carbonate ($CaCO_3$), sequestering carbon in solid form within the concrete in a manner similar to mixing carbonation.

One advantage of using CO_2 to cure concrete rather than (or in combination with) water is that different, lower-emissions formulations of cement can be used. US-based Solidia Technologies has commercialized this approach by producing a cement with significantly reduced limestone content, lowering the emissions intensity by 30% compared with OPC.[14,15] This cement will not set (harden) with conventional water-based curing; instead, it requires a mixture of CO_2 and steam. During curing, up to 30 wt% of the gaseous CO_2 is converted into solid calcium carbonate, sequestering it for the lifetime of the concrete.

Other efforts to commercialize carbonation curing for precast concrete products include CO_2-SUICOM developed by Kajima Corporation, the Chugoku Electric Power Company, Denka Company and Landes Corporation of Japan[16,17]; Canada-based CarbiCrete[18,19]; US-based CarbonBuilt (formerly CO2Concrete)[20]; Saudi Aramco/Korea Advanced Institute of Science and Technology[21,22]; and Belgium-based Orbix.[23,24]

Mixing carbonation and carbonation curing share several similarities. Importantly, unlike other forms of carbon mineralization, they do not require additional sources of calcium or magnesium because calcium is a fundamental constituent of cement. This greatly simplifies logistics and cost. Further, the only novel materials-handling challenge is providing purified CO_2, and these processes are often discussed as examples of “carbon capture, utilization and storage” (CCUS) because they store CO_2 in a useful product. Much of the attention these technologies receive is in this context. These CCUS concretes can help expand the market for captured CO_2, giving it economic value, which in turn supports implementation of CO_2 capture methods.

From this perspective, carbonation curing appears to be a more attractive CCUS option than mixing carbonation because it consumes a much larger amount of CO_2 per unit mass of concrete: amounts ranging from 20–50 $kgCO_2$ per m^3 of concrete (on the order of 0.1–0.5 wt%) have been reported in the literature.[25] An additional benefit is the fact that steam for conventional curing is energy-intensive to produce, and displacing steam with CO_2 can reduce emissions. However, some approaches to carbonation curing tend to reduce the compressive strength of the resulting concrete, meaning that more binder (OPC) is required to achieve the same compressive strength. The emissions associated with this additional binder can change the life-cycle emissions impacts of carbonation significantly, in some cases eliminating all emissions benefits entirely.[25] As a result, the attractiveness of both mixing carbonation and carbonation curing as avenues to expanded CO_2 markets must be balanced with an understanding of net CO_2 emissions impacts using careful life-cycle assessment (LCA).

The primary research and development (R&D) priority for mixing carbonation is to increase the CO_2 loading in concrete, while maintaining the compressive strength gain and other favorable properties displayed by current low-loading mixes. The primary R&D priority for carbonation curing is to develop curing protocols that will lead to increased compressive strength, allowing a reduced use of OPC.[26]

A second, related R&D priority is to better understand the impact of carbonation curing on the durability of concrete, particularly how it impacts corrosion of steel. While carbonation can increase corrosion under some circumstances, rendering concrete incompatible with steel reinforcement, this may be largely mitigated through improved process design. More research is needed to clarify this issue.[26,27]

For both mixing carbonation and carbonation curing, other R&D priorities include (1) improving the electrical energy efficiency of the process, such as the use of waste heat for drying, in order to reduce the associated emissions from consumed electricity and (2) gaining better understanding of how different supplementary cementitious materials (SCMs), such as blast furnace slag and fly ash, impact carbonation.[28]

Mixing carbonation and carbonation curing generally use purified CO_2 that is captured elsewhere. When the source of that CO_2 is biogenic, such as point-source capture from an ethanol production facility, mixing carbonation forms part of an overall method that removes CO_2 from the atmosphere and stores it in a long-duration form. This is also the case if the source of CO_2 is from direct air capture (DAC). Alternatively, if the source of CO_2 is from fossil-fuel combustion (such as point-source capture from flue gas at a coal-fired power plant) then mixing carbonation forms part of an overall method for carbon capture and storage. Mixing carbonation and carbonation curing are unlikely to be used for the direct removal of CO_2 from air without some form of initial capture and purification.

Carbon mineralization can also be used to produce **synthetic aggregate**. This process involves reacting CO_2 with alkaline feedstock containing calcium and/or magnesium, including recycled concrete and a variety of industrial wastes (see Chapter 6). This produces calcium and magnesium carbonates, which can then be used in concrete to replace mined aggregates, such as sand, gravel and crushed stone. While this substitution does not displace a large amount of emissions (the average carbon intensity of conventional aggregates is approximately 8 $kgCO_2e$ per ton, far lower than cement),[29] it can serve as an economically valuable form of CO_2 sequestration. Several companies have commercialized variations of this process. UK-based O.C.O. Technologies (formerly

Carbon8 Aggregates) provides synthetic aggregates produced from air pollution control (APC) residues and industrial CO_2.[30] US-based Blue Planet provides synthetic aggregates produced from alkaline industrial waste and dilute CO_2 in flue gas.[3]

Because the global annual aggregates market is approximately 50 Gt, the potential scale of impact from synthetic aggregates is significant.[30] Pressures from limited landfill space and high tipping fees have already led to approximately 10% of aggregates used in Europe coming from recycled or manufactured materials.[3] However, aggregates are a low-value product by weight, with crushed stone valued at approximately $12 per ton in the United States.[31] This suggests that synthetic aggregate will have difficulty competing with conventional aggregate on cost. While production of synthetic aggregate may allow more careful control over aggregate size, resulting in a more consistent product than virgin-mined aggregate, this improved feature alone is unlikely to overcome cost differentials.

A further issue for synthetic aggregate is its mechanical performance when used in concrete. Conventional aggregate is classified as fine or coarse, depending on whether particles are smaller or larger than 4.75 mm (No. 4 sieve). It is also classified by shape, such as rounded, angular or elongated. Both the size and shape of aggregates impact many important properties of concrete, including cement and water requirements in the mix, pumpability, workability and durability. Conventional aggregate is typically washed, crushed and screened to obtain desirable size and shape distributions. Synthetic aggregate will need to broadly conform to these size and shape requirements and be of sufficient mechanical strength to avoid crumbling or breaking during handling (high friability).

A closely related form of mineralization is the treatment of recycled concrete aggregates (from demolition waste) with CO_2 to improve their strength, a process known as **carbon conditioning.** This process allows these materials to be used as aggregate in new concrete mixes, providing good mechanical properties.[32,33] One approach to this process involves producing calcium bicarbonate solution via reaction of concrete demolition waste, water and captured CO_2 and then exposing crushed demolition waste aggregate particles to the solution. This leads to the precipitation of $CaCO_3$ crystals, which bond to recycled aggregate and provide it sufficient mechanical strength to allow its re-use (calcium carbonate circulation system for construction, C^4S).[34] Similar challenges regarding size, shape and friability apply to these materials, as well as to synthetic aggregates.

R&D priorities for synthetic aggregate production include optimizing (ideally reducing or eliminating) transportation of feedstock materials (such as industrial waste) and purified CO_2. To this end, increased efforts are needed to co-locate synthetic aggregate production with sources of CO_2 and industrial facilities producing alkali waste[35] (recent announcements from O.C.O. Technologies about aggregate manufacturing at a refinery are encouraging[36]). For aggregate production, a better understanding of the tradeoffs between using relatively pure CO_2 and untreated flue gas is also needed, given the improved mineralization efficiency with pure CO_2 but the associated energy and emissions penalty from CO_2 capture. For widespread market uptake, synthetic aggregate must undergo mechanical performance testing with R&D focused on mitigating any significant gaps in comparison with conventional aggregate; the same is true for carbon-conditioned recycled concrete demolition waste.

Similar to mixing carbonation and carbonation curing, the production of synthetic aggregates has primarily been proposed to use purified CO_2 that was captured elsewhere, although some methods also envision using flue gas directly (i.e., without first separating and purifying CO_2). When the source of that CO_2 is biogenic, such as point-source capture from an ethanol production facility or the use of flue gas from combustion of biomass, production of synthetic aggregate through mineralization forms part of an overall method that removes CO_2 from the atmosphere and stores it in a long-duration form. This would also be the case if the source of CO_2 were from DAC. Alternatively, if the source of CO_2 is from fossil-fuel combustion (such as point-source capture from flue gas at a coal-fired power plant) then the production of synthetic aggregate through mineralization forms part of an overall method for carbon capture and storage. The production of synthetic aggregates is unlikely to be used for the direct removal of CO_2 from air without some form of initial capture and purification.

REFERENCES

1 Johanna Lehne and Feliz Preston (Chatham House). *Making Concrete Change: Innovation in Low-carbon Cement and Concrete (Chatham House Report)*, <https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete> (2018).

2 The International Energy Agency (IEA). *Cement*, <https://www.iea.org/reports/cement> (IEA, Paris; 2020).

3 National Academies of Sciences Engineering and & Medicine (NASEM). *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*. (The National Academies Press, 2019 (https://www.nap.edu/catalog/25232/gaseous-carbon-waste-streams-utilization-status-and-research-needs)).

4 David Perilli (Global Cement). *2020 roundup for the cement multinationals*, <https://www.globalcement.com/news/item/12085-2020-roundup-for-the-cement-multinationals> (2021).

5 IBISWorld. *Industry Statistics - United States: Ready-Mix Concrete Manufacturing in the US - Number of Businesses 2005–2027*, <https://www.ibisworld.com/industry-statistics/number-of-businesses/ready-mix-concrete-manufacturing-united-states/> (Accessed September 2021).

6 The International Energy Agency (IEA). *Technology Roadmap - Low-Carbon Transition in the Cement Industry (Technology Report)*, <https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry> (IEA, Paris; 2018).

7 Jane Anderson & Alice Moncaster. Embodied carbon of concrete in buildings, Part 1: analysis of published EPD. *Buildings and Cities* **1(1)**, 198-217, doi:http://doi.org/10.5334/bc.59 (2020).

8 Hao Huang *et al.* Life-cycle assessment of emerging CO2 mineral carbonation-cured concrete blocks: Comparative analysis of CO2 reduction potential and optimization of environmental impacts. *Journal of Cleaner Production* **241**, 118359, doi:https://doi.org/10.1016/j.jclepro.2019.118359 (2019).

9 Jacob Schneider. Decarbonizing construction through carbonation. *Proceedings of the National Academy of Sciences* **117**, 12515-12517, doi:10.1073/pnas.1913867116 (https://www.pnas.org/content/117/23/12515) (2020).

10 Caleb M. Woodall, Noah McQueen, Hélène Pilorgé & Jennifer Wilcox. Utilization of mineral carbonation products: current state and potential. *Greenhouse Gases: Science and Technology* **9**, 1096-1113, doi:https://doi.org/10.1002/ghg.1940 (2019).

11 Sean Monkman, Mark MacDonald, R. Doug Hooton & Paul Sandberg. Properties and durability of concrete produced using CO2 as an accelerating admixture. *Cement and Concrete Composites* **74**, 218-224, doi:https://doi.org/10.1016/j.cemconcomp.2016.10.007 (2016).

12 Sean Monkman & Mark MacDonald. On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete. *Journal of Cleaner Production* **167**, 365-375, doi:https://doi.org/10.1016/j.jclepro.2017.08.194 (2017).

13 Duo Zhang, Zaid Ghouleh & Yixin Shao. Review on carbonation curing of cement-based materials. *Journal of CO2 Utilization* **21**, 119-131, doi:https://doi.org/10.1016/j.jcou.2017.07.003 (2017).

14 Vincent Meyer, Nick de Cristofaro, Jason Bryant & Sada Sahu. Solidia Cement an Example of Carbon Capture and Utilization. *Key Engineering Materials* **761**, 197-203, doi:https://doi.org/10.4028/www.scientific.net/KEM.761.197 (2018).

15 Vincent Meyer, Sada Sahu & Andrew Dunster. in *1st International Conference on Innovation in Low-Carbon Cement & Concrete Technology* (London, United Kingdom, 2019; https://assets.ctfassets.net/jv4d7wct8mc0/4g12cODXSpblK6Vja1FUvx/f0eb602207fd202925a35b137e818fde/2019_ILCCC_-_Properties_of_Solidia_Cement_and_Concrete_copy.pdf).

16 Challenge Zero: Innovation Challenges – Mitsubishi Corporation. *Carbon negative concrete "CO2 SUICOM"*, <https://www.challenge-zero.jp/en/casestudy/616> (Accessed September 2021).

17 K. Yoshioka *et al.* New Ecological Concrete that Reduces CO2 Emissions Below Zero Level ~ New Method for CO2 Capture and Storage ~. *Energy Procedia* **37**, 6018-6025, doi:https://doi.org/10.1016/j.egypro.2013.06.530 (2013).

18 CarbiCrete. *Technology*, <https://carbicrete.com/technology/> (Accessed September 2021).

19 Mehrdad Mahoutian, Omar Chaallal & Yixin Shao. Pilot production of steel slag masonry blocks. *Canadian Journal of Civil Engineering* **45**, 537-546, doi:10.1139/cjce-2017-0603 (2018).

20 CarbonBuilt. <https://www.carbonbuilt.com/> (Accessed September 2021).

21 Aramco. *Managing our footprint: Carbon curing*, <https://www.aramco.com/en/sustainability/climate-change/managing-our-footprint/carbon-curing> (Accessed September 2021).

22 Joon Ho Seo *et al.* CO_2 Uptake of Carbonation-Cured Cement Blended with Ground Volcanic Ash. *Materials (Basel)* **11**, 2187, doi:10.3390/ma11112187 (https://www.mdpi.com/1996-1944/11/11/2187) (2018).

23 Andrea Di Maria, Ruben Snellings, Luc Alaerts, Mieke Quaghebeur & Karel Van Acker. Environmental assessment of CO2 mineralisation for sustainable construction materials. *Int. J. Greenh. Gas Control* **93**, 102882, doi:https://doi.org/10.1016/j.ijggc.2019.102882 (2020).

24 Hadi Kazemi Kamyab, Peter Nielsen, Peter Van Mierloo & Liesbeth Horckmans. Carbstone Pavers: A Sustainable Solution for the Urban Environment. *Applied Sciences* **11**, 6418 (2021).

25 Dwarakanath Ravikumar *et al.* Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit. *Nat. Commun.* **12**, 855, doi:10.1038/s41467-021-21148-w (https://www.nature.com/articles/s41467-021-21148-w) (2021).

26 Zhen Li, Zhen He & Xiaorun Chen. The Performance of Carbonation-Cured Concrete. *Materials* **12**, 3729 (2019; https://www.mdpi.com/1996-1944/12/22/3729).

27 Duo Zhang & Yixin Shao. Enhancing Chloride Corrosion Resistance of Precast Reinforced Concrete by Carbonation Curing. *ACI Materials Journal* **116**, doi:10.14359/51714461 (2019).

28 Stefanie von Greve-Dierfeld *et al.* Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC. *Materials and Structures* **53**, 136, doi:10.1617/s11527-020-01558-w (2020).

29 Atac Bascetin, Deniz Adiguzel & Serkan Tuylu. The investigation of Co2 emissions for different rock units in the production of aggregate. *Environmental Earth Sciences* **76**, 279, doi:10.1007/s12665-017-6602-0 (https://link.springer.com/article/10.1007%2Fs12665-017-6602-0) (2017).

30 Colin D. Hills, Nimisha Tripathi & Paula J. Carey. Mineralization Technology for Carbon Capture, Utilization, and Storage. *Frontiers in Energy Research* **8**, doi:10.3389/fenrg.2020.00142 (https://www.frontiersin.org/articles/10.3389/fenrg.2020.00142/full) (2020).

31 Jason Christopher Willett (USGS). *U.S. Geological Survey, Mineral Commodity Summaries: Stone (Crushed)*, <https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-stone-crushed.pdf> (2021).

32 Vivian W. Y. Tam, Anthony Butera, Khoa N. Le & Wengui Li. Utilising CO2 technologies for recycled aggregate concrete: A critical review. *Construction and Building Materials* **250**, 118903, doi:https://doi.org/10.1016/j.conbuildmat.2020.118903 (2020).

33 Dongxing Xuan, Baojian Zhan & Chi Sun Poon. Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. *Cement and Concrete Composites* **65**, 67-74, doi:https://doi.org/10.1016/j.cemconcomp.2015.10.018 (2016).

34 Noguchi Takafumi (Nedo). *Moonshot Research and Development Program (Project Overview) – C4S Research and Development Project – C4S: Calcium Carbonate Circulation System for Construction*, <https://www.nedo.go.jp/content/100923495.pdf> (Accessed September 2021).

35 Renato Baciocchi & Giulia Costa. CO2 Utilization and Long-Term Storage in Useful Mineral Products by Carbonation of Alkaline Feedstocks. *Frontiers in Energy Research* **9**, doi:10.3389/fenrg.2021.592600 (https://www.frontiersin.org/articles/10.3389/fenrg.2021.592600/full) (2021).

36 Anthony Wright (Gasworld). *O.C.O Technology partnership paves way for Europe's first carbon negative aggregate plant*, <https://www.gasworld.com/oco-technology-partnership-paves-way-for-europes-first-carbon-negative-aggregate-plant/2021500.article> (2021).

CHAPTER 8:

CROSS-CUTTING RESEARCH NEEDS

Research and development (R&D) needs in carbon mineralization focus on (1) increasing the speed with which the reactions occur, (2) accessing a significant volume of reactive material (surficial or subsurface), (3) disposing of carbonate material produced via surficial methods, (4) measuring the total carbon impact of these approaches and (5) improving the economics of the processes. Significant cross-cutting issues are water use and safety from potentially toxic and hazardous components present in both minerals and industrial wastes.

Carbon mineralization is often viewed as a lab- and bench-scale chemical engineering research activity, but much of the associated laboratory and theoretical work has been sufficiently resolved to move forward. Large-scale demonstrations are vital for addressing systems integration, energy efficiency and cost reduction across all forms of carbon mineralization.

Priority areas for cross-cutting research are discussed below.

1. Accelerating mineralization reaction rates

Carbon mineralization fundamentally depends on combining calcium and magnesium with CO_2. However, the rate of that reaction is dependent on the structure and chemistry of the initial material and the contact mechanism with CO_2. Major topics include:

- The effect of **size, shape and crystallinity** on dissolution of minerals and industrial wastes (including, e.g., steel slag).
- The **reaction rates of mixed materials** when one mineral like brucite ($Mg(OH)_2$) dominates short-term kinetics but the majority of the material is composed of minerals with longer reaction time.
- The **reaction mechanisms for mineralization** (e.g., which mechanism controls the reaction: mineral dissolution or CO_2 transfer into a liquid layer?).
- The impact of **grinding, heating or acid pretreatments** on complex mixtures.
- The impact of **different transport fluids**—such as pure CO_2 gas, flue gas, surface waters, CO_2-rich aqueous solutions under pressure and supercritical CO_2 under pressure—on mineralization rates and outcomes.

2. Hazardous material removal and handling

Many mineral and industrial waste mixtures contain hazardous materials, including asbestos and the heavy metals chromium (Cr) and nickel (Ni). Removing these materials may be possible but, if not, the methods for handling them safely must be established. Major topics include:

- The **fate of hazardous components** during mineralization reactions.

  - Asbestos fibers with their high surface area per unit mass may rapidly and preferentially form carbonate minerals, mitigating a significant health hazard.
  - Accelerated carbon mineralization, particularly using acidic solutions, may release dissolved Ni, Cr and other potentially toxic elements and compounds.
- Methods for **pretreatment or removal of hazardous materials** prior to utilization.
  - Removing asbestos by rapidly reacting it with CO_2.
  - Pretreating minerals and industrial wastes to extract and use heavy metal components.
- The development of **protocols for safe handling** of these materials.

3. Underground injection of CO_2 in basalts and ultramafic rocks

The rate and extent of capture and long-term storage of CO_2 via carbon mineralization are challenging to measure and predict. Current knowledge is based on laboratory experiments and a limited number of field experiments with sparse sampling. Tracking the fate of CO_2 transported through reactive rocks in the subsurface will require research into the rate of underground reactions and the limiting processes that control how much CO_2 a rock can absorb. Major topics include:

- Controlled laboratory experiments on **the fate of CO_2 in basalts and ultramafic rocks.**
- **Instrumented field tests** to investigate the fate of injected CO_2, particularly in basalts and peridotites over 10–100 m distances, permitting a complete mass balance on the inputs, outputs and exchanges that may occur depending on the methods used for CO_2 transport (see below).
- Observing and controlling outcomes of **long-term, subsurface carbon mineralization** in terms of “cracking versus clogging,” formation of dissolution channels and/or permeability barriers, evolution of porosity and reactive surface area, changes in rock volume and associated deformation, and displacement of pore water.
- Practical implementation of **specific methods for transporting CO_2 through reactive materials** for subsurface mineralization. Ideas include injecting supercritical CO_2 (but this option requires an impermeable caprock), bubbling CO_2 into water in boreholes and/or pore space at depth to produce CO_2-rich aqueous fluids, or alternating injection of water and supercritical CO_2 in proportions such that the CO_2 dissolves in water at depth. Many variations and combinations are possible and testing them will require field-scale demonstration, not laboratory-scale research.
- **System integration** of CO_2 sources, heat, water exchange and heat management. Advances in this area could dramatically improve the energy, material and water efficiency of these processes.

4. Surface reaction of CO_2 with mafic and ultramafic tailings and alkaline industrial wastes

Many schemes for utilizing calcium and magnesium in rocks and industrial wastes have the same basic issues: reactivity, contact mechanism with CO_2 and permanence of products. Research efforts that identify the basic reaction mechanisms and the physical properties that affect those mechanisms will be beneficial across a wide range of processes. Major topics include:

- Understanding **the reactivity of calcium- and magnesium-bearing minerals and wastes**. Primary concerns are determing the impact of particle or crystallite size on reaction rate, separating the effects of multi-component systems on overall rates, and understanding the impacts of reacted coatings that can impede the progress of mineralization.
- Determining the **rate of CO_2 uptake from air**. In both quarried and waste materials, the rate of CO_2 uptake directly from air is affected by many minor processes, which can be hard to separate. Studies are needed to understand the controlling factors for direct atmospheric reaction with carbonation substrates.
- **Measuring and improving physical properties of beneficial products**. Conversion of wastes to beneficial materials is impacted by the physical properties of the resultant product. The key properties include strength, solubility in water, hardness and impurities.
- Exploring **additional treatment methods**. Methods of treating industrial wastes upon production may improve their use in carbon mineralization by increasing surface area or reactivity.
- Extending and improving **lifecycle emissions and cost analyses**. These analyses are needed to determine the best uses of industrial slags and wastes, especially *vis a vis* their alternative use in cements. Metrics for relative benefits should be developed and standardized.
- Determining strategies for **storage and disposal of carbonated products not suitable for utilization**. Some abundant geological materials are likely to undergo only partial mineralization over short timescales. Finding safe locations to sequester large amounts of this material—which may be an order of magnitude larger by mass than the CO_2 removed—is an important challenge to address. The oceans may provide one potential location.

5. Mineral additives to soils

Many of the proposed methods for enhanced weathering utilize powdered rock material spread on cultivated land. Basaltic lava is the rock type most commonly considered for use. The benefits are often envisioned in terms of crop yield and overall CO_2 flux, but these are extraordinarily complex topics in an active agricultural ecosystem. Additional research into interactions between added material and the soil system is needed to understand both the benefits and possible problems with this approach. Major topics include:

- Understanding **calcium and magnesium impacts on soil health**. Calcium is routinely added to some kinds of depleted soil in more readily available forms (e.g., limestone) today. Research into the mechanisms by which mafic rocks provide cations is needed. The impact of magnesium is important since it can be a problematic cation in agriculture.

- Understanding life-cycle benefits of soil mineral addition. The overall life-cycle benefits of soil addition need to be evaluated in the context of baseline conditions and alternative approaches. For instance, for the money invested, is adding powdered basalt the best way to achieve both climate and agronomic benefits?
- Identifying optimal locations. The locations where mineral additions to soil may be most beneficial need to be evaluated in terms of the two topics above.
- Identifying potential hazards. Accumulation of minor elements that occur in basalt or peridotite, such as Ni and Cr, over time may produce hazardous concentrations in soils and crops.
- Understanding impacts on microbes. Microbes are a critical part of the active soil ecosystem. Studies of the impact of minerals on microbes, and of microbes on minerals, are needed to understand ecosystem effects.

6. Monitoring CO_2 uptake in surface systems

Measuring CO_2 uptake is fairly easy in systems that create a solid product or produce purified CO_2 gas, but in systems at the surface the problem can be daunting due to the flux of CO_2 in and out of the system. For example, carbon can be lost from agricultural soil due to (1) the removal of crops, crop residues and weeds and (2) the flow of bicarbonate ions dissolved in groundwater and surface runoff into rivers and the oceans. Moreover, the effects of carbon mineralization need to be quantified against a noisy background of natural and agriculturally induced spatial and temporal variability in the carbon contents of soil and groundwater. Before conducting mineralization experiments, studies of surface systems are needed to understand background concentrations, variability and fluxes. Then a full accounting of the inputs and outputs of carbon during and after experiments is required. Major topics include:

- Measurement of **groundwater flux of carbon**, primarily in the form of bicarbonate.
- Measurement of **reduced carbon** converted to CO_2 and back, particularly by microbes.
- Large area **atmospheric CO_2 flux measurements** coupled with detailed on-ground measurements of CO_2 flux.
- The development of statistically robust sub-sampling methods that permit accurate estimation of integrated fluxes based on measurement of very small signals per unit area, potentially varying over a huge area, against a noisy background of natural processes.
  - Development of sampling methods could begin with comprehensive surveys at a very fine scale, but such surveys would not be sustainable for gigaton-scale deployment over decades.

  - The goal should be not only to assess net carbon budgets, but also to develop sub-sampling methods that return accurate flux estimates with greatly reduced sampling density and frequency.
  - This challenge is similar to that posed by evaluation of net carbon fluxes produced by "sustainable agriculture" methods (such as no-till, low-till, crop rotation and deep roots) and by addition of alkalinity to the oceans. Focusing on this generalized goal could be used to establish an overarching research program of its own.

7. Novel processes

Research is needed into new methods for reacting CO_2 with calcium and magnesium and into new products or value-added processes that could improve the economics of carbon mineralization. Major topics include:

- Novel reactors for surface treatment of rocks and wastes with concentrated CO_2, CO_2-bearing fluids or air.
- Improved methods for integration of mineralization with existing industrial process.
- Improved methods for integration of mineralization with inexpensive, partial direct air capture (DAC) to produce hybrid methods.

8. Measurement and accounting

Accurate measurement is important for any commodity traded in markets. For carbon mineralization to participate in carbon markets, accurate measurement of the carbon removed by mineralization will be essential. To facilitate large-scale financial support in carbon markets, carbon mineralization requires high-fidelity accounting approaches for carbon removal and storage quantities as well as durations. Major topics include:

- Development of **standard measurement methods for quantifying CO_2 removed** from the atmosphere by all major mineralization pathways. These should include appropriate deductions of estimated counter-factual CO_2 removal through passive (untreated) means.
- Development of **standard forecasting methods for predicting the storage duration** of mineralized CO_2 in surface and subsurface contexts and in valorized products.

9. Resource mapping

For carbon mineralization to reach its full potential as a climate change strategy, one of the most urgent needs is to identify the locations and quality of mineralization resources around the world. This includes:

- Producing **maps of ultramafic rocks** (e.g., mantle peridotite) that include their mineralogy, especially brucite and asbestos content.

- Producing **maps of mafic rocks** (e.g., basaltic lavas but also mafic intrusions) that include their mineral and glass content, as a precursor to development of estimates of their potential rates of CO_2 uptake through mineralization.
- Conducting **hydrological surveys** of volcanic provinces and peridotite localities in the US. Understanding the groundwater hydrology of these areas is crucial to discerning which of them may be practical sites for carbon mineralization, with low impact and co-benefits for local communities (see Water considerations).
- Producing **maps showing the location of legacy industrial wastes and mine tailings** and their condition and usability.
- Producing **maps of available mineral resources near agricultural areas** with soils that would benefit from additional calcium and/or magnesium.
- Expanding analysis of the **impact of varying carbon prices on the economic feasibility of mining different mineral deposits**, taking into consideration revenues from carbon-removal services through mineralization.

10. Water considerations

Many carbon mineralization methods produce, consume or cycle significant amounts of water. This could potentially result in impacts on water quality, process scale constraints due to water availability or other impacts. The role of water in carbon mineralization therefore requires more research attention to ensure that overall impacts and constraints are not problematic. Major topics include:

- Improving the understanding of the hydrological cycle in areas of high geological potential for carbon mineralization, notably volcanic provinces and peridotite localities where surface water may be limited.
- Developing advanced methods for injecting CO_2-bearing water using brackish water or seawater, minimizing demands on fresh water.
- Developing improved methods for treating and managing produced water from injection of CO_2 into the subsurface.
- Developing improved methods for modeling, monitoring and preventing potential groundwater contamination from large-scale subsurface injection.
- Developing improved methods for monitoring carbon flux in agricultural runoff as part of surficial enhanced weathering processes.

11. Social science

More work is needed to understand how carbon mineralization projects will affect a range of stakeholders, including the communities in which these activities take place. More work is also needed to help ensure that carbon mineralization can best deliver meaningful benefits to the communities where such activities occur. Priority topics for research include:

- Improving the understanding of agronomic and ecological effects of surficial carbon mineralization approaches.
- Improving the understanding of environmental and economic impacts of quarrying natural materials for carbon mineralization.
- Improving the understanding of the overall impacts of using ongoing or legacy industrial wastes for carbon mineralization at gigaton scale.
- Improving the understanding of the impact of large-scale fluid injection and subsurface mineralization, in terms of deformation, micro-seismicity and hydrology.
- Expanding assessments of the potential impact of large-scale mineralization approaches on land use and land use change, particularly for surficial enhanced weathering processes.
- Identifying employment needs and opportunities in different regions from all major mineralization processes, including specific job skills/categories in quarrying, bulk transport, chemical engineering, rock mechanics, reservoir engineering, monitoring and verification.
- Identifying and estimating overall potential economic benefits to communities from large-scale mineralization projects.

CHAPTER 9:

POLICY

Policymakers have paid scant attention to carbon mineralization as a strategy for fighting climate change. Of the more than 190 national climate action plans submitted to the UN Framework Convention on Climate Change (known as “Nationally Determined Contributions”), only one (Iceland’s) mentions carbon mineralization.[1,2] Very few climate change laws or regulations do so. Few, if any, laws or regulations that govern mining or underground injection have been adapted to reflect the potential for carbon mineralization to help meet climate change goals.

For carbon mineralization to remove CO_2 from the atmosphere at a scale of gigatons per year, supportive policies will be essential. Leading options for such policies include funding in government research and development (R&D) budgets, preferences in government procurement, recognition in emissions trading programs and incentives in tax regimes. Permitting processes for mining activities may need adjustment. International cooperation—sharing information and best practices—could accelerate progress.

Policy frameworks that engage all key stakeholders will be essential. Some carbon mineralization projects could create good high-paying jobs in mining communities and employ engineers currently employed in oil and gas extraction. Other projects could contribute to agricultural productivity (see Chapter 4). At the same time, some projects create risks of surface-water contamination and ecosystem disturbance if poorly managed. Building public support by maximizing the benefits and minimizing the risks of carbon mineralization processes will be important to their successful implementation at scale.

This chapter discusses policy options for scaling up carbon mineralization as a strategy for removing CO_2 from the atmosphere.

1. GOVERNMENT SUPPORT FOR R&D

National governments spend at least $18 billion annually on R&D for climate mitigation. These programs have played important roles in developing countless technologies in recent decades.[3]

As set forth in Chapter 8, R&D on a range of topics is important for carbon mineralization to reach its full potential for removing CO_2 from the atmosphere. Priority topics include the following:

- Reactivity of minerals and industrial wastes
- New methods for reacting CO_2 with calcium and magnesium

- Fate of CO_2 in basalts and ultramafic rocks
- Impacts of calcium and magnesium additives on soil health
- Tools for measuring and monitoring CO_2 removal from air with carbon mineralization

Much of this research involves basic science or pre-commercial topics that private companies have little, if any, incentive to fund. As a result, government funding for research on these topics will be essential. National governments, including those in the United States, Japan, the European Union, Russia and China, have historically provided most of the support for basic science and pre-commercial research.

In June 2021, ministers from more than 20 countries announced Mission Innovation 2.0, pledging "a decade of innovation to catalyze increased investment in clean energy research, development and demonstrations to deliver affordable clean energy solutions by 2030."[3] Member governments include Japan, the United States, China, the United Kingdom, Germany and Saudi Arabia. The resulting increase in government R&D budgets in these countries in the years ahead offers an opportunity to increase R&D funding for carbon mineralization.

2. GOVERNMENT PROCUREMENT

In many countries, government procurement makes up more than 10% of GDP.[4] This spending provides an important opportunity to jumpstart markets for new products with public benefits, such as CO_2 removal from air. First, government purchase contracts can provide manufacturers with an assured market, which can be especially important in securing debt capital. Second, government purchases can help establish standard technical specifications for new products, which can help catalyze efficient supply chains.

As an example, governments are major purchasers of concrete, which can be made from cement and aggregates that include mineralized carbon. Establishing strong preferences for products made with mineralized carbon in government procurement could help jumpstart markets and promote carbon mineralization as a climate solution.

3. EMISSIONS TRADING PROGRAMS

Recognizing carbon mineralization as a compliance option in emissions trading programs is one of the most important tools for realizing its full potential for climate change mitigation.

Under emissions trading programs, the right to emit requires a permit. Governments give or sell these permits to emitters, who may then trade the permits among themselves. Under many emissions trading programs, governments gradually reduce the number of permits (often called emissions allowances), thereby reducing total pollution. Emissions trading programs for CO_2 are now in place in the European Union, China, California, the northeast United States and Canada, among other places.

At present, no emissions trading programs recognize carbon mineralization as a compliance option. Such programs could do so by authorizing facilities that mineralize carbon to sell allowances equal to the CO_2 removed from the atmosphere, measured on a full life-cycle basis. Indeed such allowances might merit a premium of some kind, in light of the permanence of CO_2 removal with carbon mineralization (as compared, for example, to CO_2 removal with trees, which can burn). This approach would provide facilities that remove CO_2 from air via carbon mineralization with a financial reward for doing so.

Such an approach would require widely accepted protocols for monitoring, reporting and verifying CO_2 removal from air via carbon mineralization. Such protocols are currently lacking. Governments could accelerate development of such protocols by contributing funding to standards-setting organizations, such as the International Standards Organization (ISO) and ASTM International, as well as support for pilot projects.

4. LOW-CARBON PRODUCT STANDARDS

A low-carbon product standard sets a limit on the product's life-cycle emissions. Low-carbon fuel standards—the leading example of such an approach—have been adopted in California, Oregon, British Columbia and the European Union.

Low-carbon product standards could promote carbon mineralization in two ways.

First, low-carbon standards could be applied to products that can include mineralized carbon, such as cement and concrete (see Chapter 7). Firms that make such products would be required to steadily reduce life-cycle CO_2 emissions or to purchase credits from firms that have done so. Such a requirement could significantly increase demand for products that include mineralized carbon.

Second, carbon mineralization could be recognized as a compliance option for low-carbon standards for other products, such as fuels. CO_2 removed through carbon mineralization could be used as an offset to satisfy part of a firm's obligation to reduce the carbon footprint of a product. Limitations would likely be needed to ensure that this compliance option does not undercut the principal objective of the standard, which is to steadily reduce the carbon content of the product itself. As with emissions trading programs, widely-accepted protocols for monitoring reporting and verifying life-cycle CO_2 removals from carbon mineralization would be essential.

5. FINANCIAL INCENTIVES

Many carbon mineralization projects will be large and capital-intensive. Some may be funded in part by private capital, with investors seeking returns from the sale of products that incorporate mineralized carbon or carbon credits earned from mineralization. However, first-of-a-kind facilities are unlikely to be able to attract private capital in amounts sufficient for initial deployment at scale. (This is the classic second "valley of death" for energy technologies.)

Governments play a central role in supporting deployment of large, capital-intensive projects with climate change benefits. Government support can take several forms, including the following:

a. Tax Incentives. Tax incentives can play an important role in spurring deployment of climate mitigation technologies. In Norway, for example, generous tax incentives have helped plug-in electric vehicles capture more than 50% of new car sales in recent years. In the United States, federal tax incentives have played an important role in promoting deployment of solar and wind power.

The Section 45Q Carbon Capture Tax Credit, enacted in the United States in 2018, provides a tax credit for each ton of CO_2 sequestered. Section 45Q provides tax credits of $50 per tCO_2 sequestered in geologic formations and $35 per tCO_2 used in products, such as fuels or cement. As of this writing, the US Congress is considering several proposals to increase the value of the 45Q credit.

Tax incentives have many possible structures. They include the following:

- **Investment tax credits.** Governments could provide businesses a tax credit for a percentage of the capital costs incurred in mineralizing carbon. (This credit would be similar to the US federal government's investment tax credit for solar power, which has historically provided a tax credit of 30% of the cost of any solar installation in the United States.)
- **Production tax credits.** Governments could provide a tax credit for any products manufactured at facilities that mineralize carbon. (This credit would be somewhat similar to the US federal government's production credit for wind power, which provides a tax credit based on the kWh of wind power sold at a facility.) Because some companies do not have tax liabilities, governments can provide refundable tax credits or cash payments in lieu of tax credits under these programs.
- **Waiver of sales, value-added taxes or import taxes.** Governments could waive taxes that would otherwise be imposed on products manufactured with mineralized carbon. (Such waivers would be similar to Norway's incentives for electric vehicles, which include waivers of import and sales taxes.)

b. **Grants.** Grants are among the most direct ways to provide financial support for the low-carbon transition. Grant programs are widespread in many countries, often to assist in deploying first-of-a-kind or early-stage technologies. Governments could provide grants to help defray the capital costs associated with facilities that mineralize carbon.

c. **Loan guarantees.** Cutting the cost of debt capital can help make a project financially viable. Government loan guarantee programs seek to do this by reducing risk to lenders, resulting in lower borrowing costs. The US Department of Energy's loan guarantee programs helped launch the utility-scale solar industry in the United States, among other successes. Loan guarantees for the capital expenditures required for carbon mineralization facilities could significantly speed deployment.

6. MANDATES

Perhaps the simplest way for governments to provide incentives for carbon mineralization is to require it. For example, government mandates could require mining companies at sites with potential for carbon mineralization to take steps to realize the potential for carbon capture and storage at those sites.

Government mandates can be effective in helping reduce emissions and in building markets for clean energy products. In the United States, many state governments require utilities to purchase a minimum percentage of their power from renewable sources. In India, a similar requirement is imposed by the Ministry of New and Renewable Energy. These requirements have been important to the early growth of wind and solar power in both countries.

Other experiences with government mandates suggest caution, however. The United States federal government has required the use of cellulosic ethanol in fuel supplies for more than a decade. Nevertheless, the cellulosic ethanol industry remains in its infancy. Waivers to that requirement have been granted on a regular basis. Technology-forcing requirements—in which governments require private actors to meet standards that are not yet technically achievable—have been successful in some instances but not in others.

7. ENVIRONMENTAL, SOCIAL AND GOVERNANCE ISSUES

Carbon mineralization projects can have far-reaching impacts beyond removing CO_2 from the atmosphere. Potential environmental impacts range from positive (such as soil quality enhancement) to negative (such as groundwater contamination and ecosystem disturbance). Social impacts could also be positive (such as job creation or preservation) or negative (such as disrupting communities or appropriating project benefits without compensating local stake holders).

In part as a result, carbon mineralization projects may be subject to extensive regulatory oversight in some countries. *Ex situ* projects may be subject to mining sector regulations and permit requirements on diverse topics ranging from groundwater protection to hazardous waste management to foreign ownership to financial transparency.[5,6] (The Extractive Industries Transparency Initiative (EITI), for example, promotes “the disclosure of information along the extractive industry value chain from the point of extraction, to how revenues make their way through the government, and how they benefit the public.”[7] More than 55 countries have pledged to meet EITI’s standards.) *In situ* projects may be subject to regulations on underground injection (likely designed for unrelated purposes).

As governments consider strategies for scaling up carbon mineralization for CO_2 removal from air, regulatory issues will require considerable attention. Governments could support pilot and demonstration projects to help assess a range of regulatory issues. Governments could also ask relevant ministries and departments to examine the overall regulatory environment for carbon mineralization projects and recommend whether modifications may be appropriate. Expedited permitting could be considered for projects with significant potential to remove carbon from the atmosphere and create jobs (while being careful to avoid projects that could pollute local environments or impair carbon mineralization projects’ social license to operate).

Engaging communities most directly affected by carbon mineralization projects will be essential. Without support from such communities, carbon mineralization projects are unlikely to reach the scale needed for meaningful climate change impacts. Ensuring that carbon mineralization projects deliver both local and global benefits will be important to their long-term success.

8. INTERNATIONAL COOPERATION

Opportunities for CO_2 removal through carbon mineralization are widely dispersed around the globe (see Chapters 1 and 2). International cooperation in mapping mineral resources, sharing best practices and developing MRV protocols could help accelerate carbon mineralization as a climate mitigation strategy.

A number of international organizations could launch or deepen work on this topic. One potential venue is the Clean Energy Ministerial, which hosts initiatives sponsored by interested governments. Countries with significant carbon mineralization potential—including the United States, Japan, Canada, India, the United Arab Emirates and Saudi Arabia—could launch a Clean Energy Ministerial initiative to work together on this topic. Another possible venue is the UN Framework Convention on Climate Change, which could task a subsidiary body to gather information on this topic from Member States, including information on mineral resources that are especially well-suited to carbon mineralization. Finally, the Intergovernmental Panel on Climate Change (IPCC) could expand coverage of carbon mineralization in future assessments.

REFERENCES

1 United Nations Framework Convention on Climate Change (UNFCCC). *Nationally Determined Contributions (NDCs): The Paris Agreement and NDCs*, <https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs> (Accessed September 2021).

2 United Nations Framework Convention on Climate Change (UNFCCC). *NDC Registry (Interim): The Latest Submissions*, <https://www4.unfccc.int/sites/ndcstaging/Pages/LatestSubmissions.aspx> (Accessed September 2021).

3 Mission Innovation. *Mission Innovation launches a decade of clean energy innovation to accelerate achieving the Paris Agreement Goals*, <http://mission-innovation.net/2021/06/02/decade-clean-energy-innovation-mi-6/> (2021).

4 Esteban Ortiz-Ospina and Max Roser. *"Government Spending" (Published online at OurWorldInData.org)*, <https://ourworldindata.org/government-spending > (2016; Online resource; accessed September 2021).

5 Investment Climate Advisory Services – World Bank Group. *Sector Licensing Studies – Mining Sector*, <https://openknowledge.worldbank.org/bitstream/handle/10986/27787/587890WP0Secto1BOX353819B001PUBLIC1.pdf?sequence=1&isAllowed=y> (Accessed September 2021).

6 Baker McKenzie. *Global Mining Guide*, <https://resourcehub.bakermckenzie.com/en/resources/global-mining-guide> (Accessed September 2021).

CHAPTER 10:

COMPARISON WITH DIRECT AIR CAPTURE

As a strategy for removing CO_2 from the atmosphere, carbon mineralization shares many characteristics with direct air capture (DAC). Both are early stage and expensive. Both have clear pathways to reduce costs, can be deployed in many locations around the world and show considerable promise in helping to achieve net-zero emissions.

The two strategies also have important differences. Carbon mineralization processes typically require far less energy than DAC. Some carbon mineralization processes offer ancillary benefits not available from DAC. Carbon mineralization processes inherently provide a mechanism for long-term storage of CO_2, which DAC processes do not. However, measurement and verification of CO_2 removal is more difficult for some carbon mineralization methods than for DAC. Also, more scientific research is required for full deployment of carbon mineralization than for DAC.

The following table summarizes key similarities and differences.

Table 10-1. Comparisons between direct air capture (DAC) and carbon mineralization.

	Direct Air Capture	Carbon Mineralization
Process type	Purely engineered process	Accelerated natural process
Potential for abatement	Effectively limitless (10–20 trillion tCO_2 storage in conventional reservoirs)	Effectively limitless (>10,000 trillion tCO_2 storage potential)
Potential to achieve gigaton-scale carbon removal before 2040	High	High
Geographic range	Very broad	Very broad
Cost today	Above $200/ton	Above $200/ton
Likelihood of costs below $150/ton before 2030	High	High
Requirement for energy inputs	Very high (~250 MW/Mton) – must be near-zero carbon footprint	Zero to medium – must be near-zero carbon footprint
Land-use requirement for process	Small (0.1 km^2/Mt)	Varies widely (1–400 km^2/Mt)
Land-use requirement for low-carbon energy	Varies widely (0.1–100 km^2/Mt)	Varies widely
Uses Earth-abundant materials	In some cases	Yes
Ancillary benefits beyond climate mitigation	Limited – some fresh-water production	Substantial in some approaches, including remediation of hazardous materials, building material production and more
Potential additional environmental concerns	Limited	Medium
Technical Readiness Level	TRL 8–9 (established companies) TRL 5 (emerging companies) TRL 1–2 (new approaches)	TRL 5 (emerging companies) TRL 1–2 (new approaches)
Need for additional scientific research	Limited	Substantial

A few similarities and differences are especially noteworthy:

- **Cost:** For both strategies, costs today are fairly high in practice—above $200 per tCO$_2$. Although published estimates for potential costs are much lower (e.g., <$150 per ton for DAC, <$100 per ton for carbon mineralization), these lower costs have not been achieved in real projects or active markets. In both cases, the thermodynamic limits permit very low costs (~$18 per ton for DAC, $10 per ton for carbon mineralization), and there is enormous potential to reduce costs significantly and quickly for both strategies through innovation and design.
- **Technical readiness:** Both strategies are relatively immature. Neither has mature technical pathways or contracts to deliver CO$_2$ removal greater than 10,000 tons per year. DAC is somewhat more mature: three companies have commissioned projects and have commercial contracts. In contrast, while a few carbon mineralization companies have announced substantial pilot projects, they are still quite early in technical development.
- **Geographic range:** Both strategies can take advantage of different geological and energy resources around the world. They can operate under different temperature and humidity conditions, store CO$_2$ in varying geological sites and have access to different low-carbon energy resources. While the specific conditions will affect cost and performance, a mixture of pilots and demonstrations around the world could provide key information to companies, governments, investors and innovators regarding performance under a range of conditions.

All three of these points suggest that both carbon mineralization and DAC are good candidates for an innovation agenda. Specifically, research should focus on cost reduction and a mixture of pilot and demonstration projects. This would grow companies, foster competition and validate designs and business models. Ideally, nations and projects around the world should share findings and results of innovation with the goal of accelerating learning and time to market.

A comparison of carbon mineralization and DAC suggests several important research directions:

- **Energy Consumption:** This is the most dramatic difference between the two technologies. Carbon mineralization provides much of the required energy from the chemistry of the rocks or slag, while DAC requires energy input entirely from an external source. The amount of energy DAC requires varies depending on the technology, but NASEM (2019)[1] estimated about 250 MW per 1 million tons of CO$_2$ removed per year (with a range of 100–500 MW). Thus, mineralization offers a pathway to carbon removal that requires less clean energy development.
  - The major R&D activity in this area is to further refine the energy needs of the two practices, particularly around supply chains.
- **Accounting:** The clear accounting associated with DAC coupled with geologic storage is a strong advantage for DAC. The amount of CO$_2$ removed and stored is easily measured by conventional chemical monitoring systems, and geologic storage has been extensively evaluated for the control and monitoring of leaks from deep storage. Thus, errors in the accounting of DAC should be negligible.

Accounting for mineralization is significantly more difficult when the CO_2 comes from atmospheric uptake. The formation of solid carbonates is equivalent to geologic storage in its simplicity and accuracy of measurement, but in most systems open to the air, a significant amount of the captured CO_2 may leave the location in crops, crop residues, weeds and as bicarbonate ions dissolved in water. The bicarbonate ions are actually good for capture efficiency since two bicarbonate ions are required for charge balance of each dissolved ion of calcium or magnesium. However, monitoring the concentration and flux of bicarbonate in groundwater and surface runoff is a key research challenge, especially for agricultural applications and ocean-based systems.

The major R&D activity in this category is to improve the monitoring and life-cycle assessment (LCA) for mineralization approaches.

- **Land Use:** Availability of land area for CO_2-removal (CDR) technologies is likely to be a major limit on their deployment. Here there is no obvious winner because the two approaches use land in very different ways. DAC's direct footprint is small, almost negligible. LLNL (2019)2 estimated the land area footprints for solvent- and sorbent-mediated DAC applied in California set forth in the table below.

Table 10-2. Land area footprints for direct air capture and energy joint facilities capturing 1 million tons of CO_2 per year. In the case of the solvents, only solar and wind are powering the electric component of the energy, with natural gas powering the thermal component.[1-4]

	Natural Gas		Solar		Wind	
	Sorb. Effectively limitless (10–20 trillion tCO_2 storage in conventional reservoirs)	Solv. Limited	Sorb. Effectively limitless (>10,000 trillion tCO_2 storage potential)	Solv. (NG) Substantial	Sorb.	Solv. (NG)
Energy Footprint [km^2]	0.26	0.43	21	5 (0.37)	217	51 (0.37)
Direct Air Capture Footprint [km^2]	2	7	2	7	2	7
Total Land Area Footprint [km^2]	2.3	7.4	23	12.4	250	58.4

However, if solar power is used to drive DAC systems, the land footprint is significant: 12–23 km^2 per million tons of CO_2 removal capacity per year. For example, removing 1 $GtCO_2$ from air with a DAC system covering 23 km^2 would require 23,000 km^2 for photovoltaic power generation.

There are many ways to consider the land area required for mineralization. Kelemen et al. (2020)[5] made a simple estimate for the long-term weathering of exposed ultramafic rock, capturing and storing about 2.5 $kgCO_2$ per m^2 of exposed fine-grained material. Thus, removing 1 $GtCO_2$ from air by this simple process would require 400,000 km^2 of surface. A much more intensive process using stacked material in greenhouses is envisioned by Myers and Nakagagi (2020).[6] They estimate land requirements of about 1000 km^2 to remove 1 $GtCO_2$ from air per year.

The land area requirements for mineralization are thus dependent on the method used and its efficiency, unlike current knowledge of land use for DAC, which appears more certain. In any case, both require significant land area. Of immediate interest is whether the land required in both case could be put to dual use. The comparative value of the land for other purposes will also be a significant factor.

The major R&D activity in this topic is to evaluate the true land-use requirements for various carbon mineralization approaches and to compare the availability of land for both DAC and carbon mineralization to determine how much land could realistically be committed for those purposes.

The foregoing suggests that DAC faces several challenges that carbon mineralization does not.

- Carbon mineralization processes generally use standard equipment widely available around the world. DAC processes, in contrast, often require specialized equipment that is not widely commoditized and lacks a broad manufacturing base. Obtaining equipment and securing critical materials could be a significant bottleneck to scaling up DAC.[7]
- Carbon mineralization processes generally use far less energy than DAC, imposing fewer constraints with respect to the availability of low-carbon energy

For both carbon mineralization and DAC, the required skill sets for workers are likely to be similar to those required for current jobs in oil and gas, making labor unlikely to be a major bottleneck. Indeed, the potential to create good-paying jobs for oil and gas workers may help create political support for both carbon mineralization and DAC, accelerating their scale-up.

Carbon mineralization and DAC could both provide substantial CO_2 removal and climate mitigation once scaled. The two strategies can also complement each other and provide important synergies. This is already underway at the Climeworks-CarbFix project,[8,9] in which carbon mineralization and DAC work in tandem. Similar positive synergies are provided in the Heirloom process[10] (where carbon mineralization is the mechanism for DAC) and the 44.01 project[11] (which combines carbon mineralization and DAC in the deserts of northwestern Oman).

REFERENCES

1 National Academies of Sciences (Engineering and Medicine) (NASEM). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. (Washington, DC: The National Academies Press, 2019; https://doi.org/10.17226/25259).

2 Joshuah K. Stolaroff Sarah E. Baker, George Peridas, Simon H. Pang, Hannah *et al.* Getting to Neutral: Options for Negative Carbon Emissions in California. (2020 (Lawrence Livermore National Laboratory, LLNL-TR-796100); https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf).

3 J Wilcox, B Kolosz & J Freeman. *CDR Primer*, <https://cdrprimer.org > (2021).

4 Energy Futures Initiative (EFI). *Clearning the Air: A Federal R&D Initiative and Management Plan for Carbon Dioxide Removal Technologies*, <https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5d899dcd22a4747095bc04d5/1569299950841/EFI+Clearing+the+Air+Summary.pdf> (2019).

5 Peter B. Kelemen *et al.* Engineered carbon mineralization in ultramafic rocks for CO2 removal from air: Review and new insights. *Chem. Geol.* **550**, 119628, doi:https://doi.org/10.1016/j.chemgeo.2020.119628 (2020).

6 Corey Myers & Takao Nakagaki. Direct mineralization of atmospheric CO2 using natural rocks in Japan. *Environ. Res. Lett.* **15**, 124018, doi:10.1088/1748-9326/abc217 (2020).

7 Noah McQueen *et al.* A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. *Progress in Energy* **3**, 032001, doi:10.1088/2516-1083/abf1ce (2021).

8 Climeworks. <https://climeworks.com> (Accessed September 2021).

9 CarbFix. <https://www.carbfix.com> (Accessed September 2021).

10 Heirloom Carbon Technologies. <https://www.heirloomcarbon.com/> (Accessed September 2021).

11 44.01. <https://4401.earth/> (Accessed September 2021).

CHAPTER 11:

FINDINGS AND RECOMMENDATIONS

FINDINGS

FINDING 1: Carbon mineralization has the potential to permanently remove and sequester many gigatons of CO_2 from the atmosphere each year. Carbon mineralization can remove CO_2 directly from the atmosphere and permanently store that CO_2 by incorporating it into rocks. Carbon mineralization can also permanently store CO_2 captured from point sources, such as coal power plants and industrial facilities, again by incorporating that CO_2 into rocks. With strong and sustained policy support from governments around the world, carbon mineralization processes have the potential to remove 1 $GtCO_2$ from the atmosphere per year by 2035 and 10 $GtCO_2$ per year by 2050. More research is needed to define conditions under which carbon mineralization processes could achieve this potential.

FINDING 2: As a strategy for carbon removal and sequestration, carbon mineralization has many strengths. First, rock types suitable for carbon mineralization are found in dozens of countries. Second, chemical reactions that mineralize CO_2 do not require energy inputs. Third, once CO_2 is incorporated into rocks (becoming part of a carbonate mineral), that CO_2 is sequestered for millennia. The combination of widely available resources, favorable thermodynamics and permanent CO_2 storage makes carbon mineralization an important potential strategy for meeting climate change goals.

FINDING 3: As a strategy for carbon removal and sequestration, carbon mineralization also has several challenges. First, most natural carbon mineralization happens very slowly. Second, the distribution of optimal mineral resources is only coarsely understood. Third, while some products of carbon mineralization have commercial value, those values are typically low. Finally, carbon mineralization for climate mitigation is not yet practiced at large scale.

FINDING 4: Carbon mineralization is not one pathway—it is multiple pathways. All carbon mineralization approaches are based on reacting CO_2 with minerals in some form. However, the source of CO_2 and feedstock, the nature of the mineralization processes and the fate of the resulting carbonate minerals all vary dramatically from one pathway to another. CO_2 may come directly from the air or from point-source carbon capture systems. Feedstock materials may be found in geologic formations, mine tailings or industrial wastes. The mineralization process may involve transporting CO_2 to minerals rich in magnesium, calcium or similar elements (e.g., with pipelines to quarries) or exposing fine-grained materials to weathering (e.g., with powdered rock applied to farm fields). In some cases, the carbonate minerals produced have economic value and can be used in construction or agriculture, while in other cases the minerals remain sequestered in the subsurface.

FINDING 5: Carbon mineralization receives little recognition or support in climate change policies around the world. Only one nation (Iceland) mentions carbon mineralization in its Nationally Determined Contribution under the Paris Agreement. Investment in research and development (R&D) on carbon mineralization is minimal. Carbon markets, including the European Emissions Trading System and the California Low-Carbon Fuel Standard, do not provide credit for carbon mineralization. Few if any jurisdictions offer tax incentives or subsidies for carbon mineralization.

FINDING 6: Current scientific knowledge and technical experience are sufficient to support carbon mineralization projects at the pilot and demonstration scale today. The large and readily accessible literature on mineral structure, reaction kinetics and thermodynamics provides a strong foundation for such projects. Conventional mining operations can help in assessing the engineering requirements and costs. Methods for monitoring and verifying carbon removal and storage are available for many carbon mineralization strategies. This body of knowledge and experience can help carbon mineralization play an important role in meeting climate change goals on time.

FINDING 7: The key technical challenges in carbon mineralization are speeding up the chemical reaction between atmospheric CO_2 and minerals, maximizing the CO_2 content of mineralized materials and minimizing the space required for permanent storage. Although some rocks and minerals react with CO_2 quickly, most do not under normal circumstances. Achieving economically viable mineralization techniques requires processes to accelerate these reactions, which can include grinding, heating and chemical treatment. Maximizing the CO_2 content of mineralized materials can reduce the amount of rock or waste material required, the cost of obtaining and grinding that material, and the volume of carbonated material that must be stored permanently. For surficial carbon mineralization, low-cost, low-impact space for permanent storage is essential.

FINDING 8: Measurement and verification tools today are sufficient for carbon mineralization approaches (including ex situ conversion of main tailings) and insufficient for others (including enhanced rock weathering). Measurement and verification methodologies for *ex situ* conversion of mine tailings and alkali wastes provide sufficient clarity for attribution and permitting today. Those for *in situ* CO_2 injection may suffice but require validation. Those for enhanced weathering of minerals added to fields, beaches, the oceans or sedimentary systems currently lack the precision and accuracy needed to certify and permit CO_2 reduction or removal. Refinement of measurement and verification tools for carbon mineralization processes should be a priority.

FINDING 9: Field pilots and demonstration projects could significantly improve understanding of the potential impacts and costs of carbon mineralization processes, while improving monitoring and verification methods. The core questions regarding scale-up and deployment of carbon mineralization are operational and must be addressed in field pilots and demonstration projects. (Lab and benchtop research are insufficient.) Data and experience from field pilots and demonstration projects will provide important insights regarding the cost, efficacy and scale of CO_2 removal and storage with carbon mineralization processes. Some field pilots and demonstration projects could be launched quickly (e.g., in operating mines under public-private partnership agreements). Others would require more time in preparation. Field pilots and demonstration projects are necessary precursors to investment, commercialization and scale up.

RECOMMENDATIONS

Recommendation 1: ***Policy makers should add carbon mineralization to the portfolio of climate change mitigation options.*** *Governments should consider a range of options, including tax incentives, procurement programs that favor products of carbon mineralization, and recognition of carbon mineralization as a compliance option in emissions trading programs. Governments should examine the regulatory framework for carbon mineralization activities, exploring ways to expedite permitting while protecting public health and safety. Many nations should include carbon mineralization in their Nationally Determined Contributions under the Paris Agreement.*

Recommendation 2: ***Governments and companies should invest in R&D on carbon mineralization****. This should include basic and applied science, engineering tests and development, novel reactor design, novel approach development, and dedicated field pilots. Priority topics should include (1) assessment of geological resources and industrial wastes, with great detail and high fidelity, (2) development and refining of measurement and verification protocols and (3) analysis of potential environmental demands (e.g., water requirements) and consequences (e.g., heavy metal contamination). Most importantly, R&D programs should include field pilots and demonstrations, using public-private partnerships where appropriate.*

Recommendation 3: *Mining companies and manufacturers should seek opportunities for carbon mineralization in their exploration and production activities. Companies that extract mineral resources from mafic and ultramafic rock bodies (e.g., nickel, chromium and diamond mines) should consider assessing the carbon mineralization resources in tailings and host rock and modifying the treatment and disposal of tailings. This assessment may entail new assays within existing operations and expanded assays during exploration that identify potential lodes and minerals suited to rapid mineralization (e.g., rocks rich in brucite and/or olivine). Companies that produce alkaline metal wastes (e.g., primary iron production and fly ash) should consider processes and approaches that can reduce or balance their emissions. Both classes of companies should develop methodologies to validate and certify* CO_2 *capture and storage, as well as contracting* CO_2 *removal–specific products and services.*

Recommendation 4: ***Governments and companies with net-zero commitments should consider carbon mineralization as part of their portfolio of options.*** *As national and subnational governments consider ways to meet net-zero targets in the years ahead, carbon mineralization provides an attractive option for offsetting emissions that are difficult or impossible to eliminate. For companies intending to reduce Scope 1 emissions through point-source carbon capture and storage, mineralization may offer advantages over injection into saline aquifers. For companies intending to procure* CO_2 *removal services to offset remaining emissions, carbon mineralization using* CO_2 *captured from the atmosphere or biogenic sources may offer reliable, additional, long-duration* CO_2 *removal.*

Carbon Mineralization Roadmap

	Near-term **(1-3 years)**	Medium-term **(2-8 years)**	Long-term **(4-15 years)**
FUNDAMENTAL AND APPLIED RD&D	Launch 50 carbon mineralization pilot projects across multiple pathways	Launch 25 full-scale carbon mineralization projects	100 megaton+ scale carbon mineralization projects in operation globally
	Establish methods for assessing powdered rock reactivity for ERW	Study interactions between mineral additives (powdered rock) and soils	Launch 25 new pilot projects with advanced mineralization mechanisms
	Develop methods for hazardous material removal and handling	Develop advanced/novel mineralization processes	
	Map geological resource and alkaline industrial waste resource	Develop improved methods for monitoring carbon uptake in surface systems	
	Study job-creation potential and timelines for deployment scale-up	Conduct fundamental R&D on increasing mineralization reaction rates and reducing freshwater consumption/use	

Carbon Mineralization Roadmap

	Near-term **(1-3 years)**	Medium-term **(2-8 years)**	Long-term **(4-15 years)**
POLICY & STANDARDS	Significantly increase government R&D budgets for carbon mineralization	Continue to significantly increase government R&D budgets for carbon mineralization	Sustain high government R&D budets for carbon mineralization
	Establish carbon accounting methodologies for measuring rates of CO_2 removal	Codify international standards for mineralization carbon accounting	Monitor large-scale projects to measure impact on policy goals
	Include carbon mineralization as compliance option in emissions trading programs	Expand jurisdictions with carbon mineralization as a compliance option in emissions trading programs	Increase carbon floor prices in jurisdictions with emissions trading programs
	Conduct regulatory reviews to streamline relevant permitting processes	Adopt streamlined permitting processes that protect public health and promote carbon mineralization	Provide policy support for retrofitting existing mines to produce mineralization feedstock
	Establish programs for community consultation and stakeholder engagement	Provide preferences to carbon mineralization products in government procurement	

Carbon Mineralization Roadmap

	Near-term **(1-3 years)**	Medium-term **(2-8 years)**	Long-term **(4-15 years)**
CORPORATE LEADERSHIP	Mining industry adopts net-zero emissions goal	Leading mining companies meet net-zero emissions goal	Mining industry meets net-zero emissions goal
	Major producers of alkaline industrial waste launch mineralization line of business	Leading mining companies launch carbon mineralization lines of business	Leading mining companies scale carbon mineralization lines of business
	Best practices for ERW established and adopted in agriculture industry	Unutilized alkaline industrial waste cut by 50%, partly through mineralization	Unutilized alkaline industrial waste cut by 80%, partly through mineralization
	Major companies begin to procure voluntary offsets from carbon mineralization	> 10 megatons/year of carbon mineralization procured by voluntary market	> 100 megatons/year of carbon mineralization procured by voluntary market

DISCLOSURE STATEMENT

Names of companies and descriptions of their activities are provided at several places in this Roadmap to better inform the reader. The co-authors have no affiliation with any of the companies mentioned in the Roadmap, except that (1) Peter Kelemen is an advisor to and shareholder in Heirloom Carbon Technologies and 44.01 and (2) Ian Power and Sasha Wilson are currently receiving research funding from De Beers and Rio Tinto.

DISCLAIMER

Roger Aines and Briana Schmidt contributed to the technical evaluations but not the policy recommendations in this document.

CITATION

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